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F-111 Adhesive Bonded Repairs Assessment Program - Progress Report 2: Analysis of FM300-2K Repairs

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ABSTRACT

It is estimated that over 5,000 adhesively bonded repairs (ABRs) have been applied to the Royal Australian Air Force (RAAF) F-111 aircraft over the last twenty five years, mainly to honeycomb sandwich panels. Retirement of the fleet in December 2010 presented a unique opportunity to evaluate the integrity of a large number of airworthy ABRs. Consequently, DSTO in partnership with the RAAF, through ASI at DGTA and with the assistance of Boeing Australia developed a program to assess the condition of the F-111 ABRs. The F-111 Adhesive Bonded Repair Assessment Program (FABRAP) was established in mid 2010 and initial field testing was carried out from October 2010. The current report provides an update on the analysis of the results from the field level testing undertaken between October 2010 and July 2012 on repairs to honeycomb structure which used FM300-2K adhesive and RAAF approved surface treatments and application procedures. The investigation indicates that when repairs were applied according to RAAF procedures and with qualified technicians in fit-for-purpose facilities, that bond strength did not degrade as a result of either long term environmental exposure or service exposure or both.

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F-111 Adhesive Bonded Repairs Assessment Program - Progress Report 2: Analysis of FM300-2K Repairs

Executive Summary

Adhesive bonded repair technology (ABRT) has been used extensively by the Australian Defence Force (ADF) for the through-life-support of secondary and tertiary aircraft structures, where failure of the repair would not result in structural failure of the aircraft. This has resulted in significant cost savings and increased aircraft availability. Wider adoption of ABRT, particularly on primary aircraft structure that is critical to the safety of the aircraft, has the potential to increase these benefits. A major impediment to the adoption of ABRT for primary aircraft structure is the difficulty in obtaining airworthiness certification. The two major reasons for this are:

- the lack of a non-destructive inspection (NDI) technique that can assess the in-service integrity of a bonded joint, and
- uncertainty regarding the environmental durability of adhesive bonds.

It is estimated that over 5,000 adhesively bonded repairs (ABRs) have been applied to the Royal Australian Air Force (RAAF) F-111 aircraft over the last twenty five years, mainly to honeycomb sandwich panels. Retirement of the fleet in December 2010 presented a unique opportunity to evaluate the integrity of a large number of airworthy ABRs.

Consequently, the Defence Science and Technology Organisation (DSTO) in partnership with the RAAF, through Aircraft Structural Integrity (ASI) Program at the Director General Technical Airworthiness (DGTA) and with the assistance of Boeing Australia developed a program to assess the condition of the F-111 ABRs. The F-111 Adhesive Bonded Repair Assessment Program (FABRAP) was established in mid-2010 and initial field testing was carried out from October 2010. The primary aim of FABRAP was to evaluate the environmental durability of the adhesive bonded repairs applied to F-111 honeycomb panel structure in which processes, materials and technical training were based on methods prescribed in DEFAUST9005 and detailed in AAP7021.016-1 and AAP7021.016-2.

The current report provides an update on the analysis of the results from the field level testing undertaken between October 2010 and July 2012. The major conclusions to be drawn from the work to date are detailed below.

The Pneumatic Adhesion Tensile Testing Instrument employed to examine the repair strength, known as the PATTI, has proved reliable for estimating bond strength and has provided good indications in cases where bond degradation has occurred. When the PATTI test results were filtered for statistically significant numbers of tests and erroneous results, it was clear that the bond strength of repairs was not affected by either service life or total accumulated hours since application. This indicates that when repairs were applied according to RAAF procedures and with qualified technicians in fit-for-purpose facilities, that bond strength will not degrade as a result of either long-term environmental exposure or service exposure or both. The results from the initial analysis should provide improved confidence in the application of bonded repair technology in the maintenance of aircraft structure.

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Eudora Yeo graduated BCom/BE (Hons) from Monash University and joined the Air Vehicles Division in 2002. She is involved in research on environmental effects on adhesive bond durability and composite materials relevant to current and future ADF platforms.

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1. Introduction

Adhesive bonded repair technology (ABRT) has been used extensively by the Australian Defence Force (ADF) for the through-life-support of secondary and tertiary aircraft structures, where failure of the repair would not result in structural failure of the aircraft. This has resulted in significant cost savings and increased aircraft availability. Wider adoption of ABRT, particularly on primary aircraft structure that is critical to the safety of the aircraft, has the potential to increase these benefits.

A major impediment to the adoption of ABRT for primary aircraft structure is the difficulty in obtaining airworthiness certification. The two major reasons for this are;

- the lack of a non-destructive inspection (NDI) technique that can assess the in-service integrity of a bonded joint, and
- uncertainty regarding the environmental durability of adhesive bonds.

It is estimated that over 5,000 adhesively bonded repairs (ABRs) have been applied to the Royal Australian Air Force (RAAF) F-111 aircraft over the last twenty five years, mainly to honeycomb sandwich panels. Retirement of the fleet in December 2010 presented a unique opportunity to evaluate the integrity of a large number of airworthy ABRs.

Consequently, DSTO in partnership with the RAAF, through Aircraft Structural Integrity (ASI) Section at the Directorate General Technical Airworthiness (DGTA), and with the assistance of Boeing Australia, developed a program to assess the condition of the F-111 ABRs. The F-111 Adhesive Bonded Repair Assessment Program (FABRAP) was established in mid 2010 and initial field testing was carried out from October 2010. The primary aim of FABRAP was to evaluate the environmental durability of the adhesive bonded repairs applied to F-111 honeycomb panel structure in which processes, materials and technical training were based on methods prescribed in DEFAUST9005 [1] and detailed in AAP7021.016-1 [2]and AAP7021.016-2 [3] RAAF Air Publications.

A previous report [4] provided an update on the analysis of the results from the field-level testing undertaken between October 2010 and May 2011, focussing on repairs applied using FM300 adhesive. A range of variables were examined to determine if any significant factors affected repair strength. The previous report examined major factors including the following:

- Repair location on the aircraft structure, such as upper, lower or side surface
- Repair age based on either total accumulated time or total number of flight hours since application
- The influence of substructure stiffness, primarily the effect of panel skin thickness

The previous report found that while repair location on the aircraft structure may have had some effect on the measured repair strength (due to the potential effect of substrate curvature on test piston misalignment), repair location did not appear to be a major factor influencing the measured repair strength. The previous report also found that the repair age, based on either total accumulated time or total number of flight hours since application, did not appear to have an effect on the measured repair strength. However,

the substructure stiffness was found to have a significant influence on the measured repair strength.

The current report provides an update on the analysis of the results from the field-level testing undertaken between October 2010 and July 2012, with details of the testing phases provided below. In this third progress report, analysis has been limited to bonded repairs in which FM300-2K adhesive was used. FM300-2K has a distinctive dark yellow colour, and it is known that the adhesive was introduced for bonded repairs in 1997 at which time the current bonding procedures prescribed in DEFAUST9005 [1] became established in RAAF bonded repairs at RAAF Amberley.

2. Test Phases and Background

A brief background to the typical repairs examined and the strength testing and analysis methods employed is provided. F-111 structure is comprised of large areas of honeycomb-core stiffened aluminium panels, which exist across the fuselage and are used for most control surfaces. The honeycomb panels typically are manufactured by adhesively bonding an upper and lower aluminium skin to aluminium honeycomb-core. The structure provides added stiffness to the airframe and reduces the weight of control surfaces, but is prone to impact damage. To re-establish airworthiness of an impact-damaged component, one of the typical repair techniques requires removal of the damaged skin and honeycomb core. New core is adhesively bonded back in place and an aluminium doubler of similar thickness to the skin thickness is bonded over the exposed core with a prescribed overlap length (Figure 1). The purpose of the bonded repair analysis program was to interrogate the condition of the adhesive bond between the bonded doubler and the existing aluminium skin. The method for bonding the skin used processes and materials defined in DEFUST9005 [1] and AAP7021.016-2 [3] RAAF Air Publications and special purpose facilities at RAAF Amberley with trained technicians. The condition of the doubler-bond provides an opportunity to establish the reliability of the bonding processes used and their resistance to typical service environments experienced by F-111 aircraft in Northern Australia.

The primary method used to interrogate the strength of the bonded doubler was with a Pneumatic Adhesion Tensile Testing Instrument (PATTI) [5]. Half-inch diameter stubs were bonded to the aluminium skin followed by a hole being routed out around the outside of the stub, through the doubler thickness. A piston attached to the stub was then pressurised and the burst pressure recorded (Figure 2). The pull-off tensile strength was then calculated and recorded. Depending on the repair location and size, between 1 and more than 10 test stubs may have been used to estimate the repair residual-strength. Subsequently, the doubler was peeled from the panel surface and photographed to determine if any anomalous areas existed.

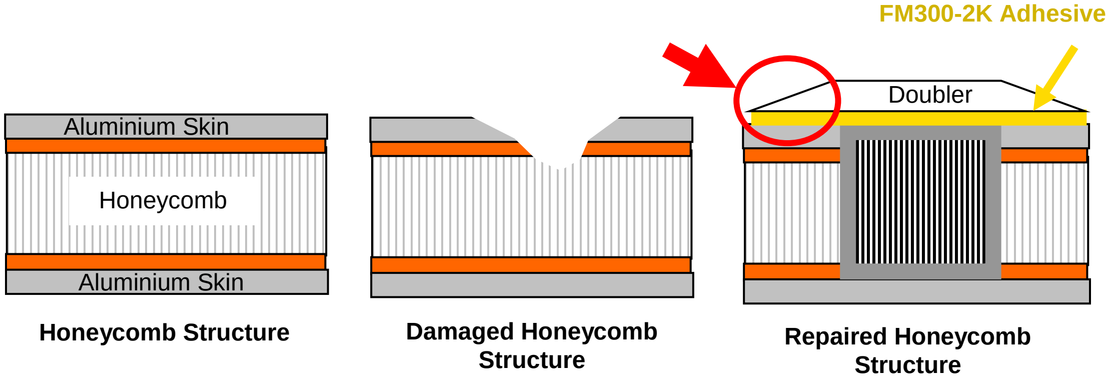

Figure 1 *Typical honeycomb structure present on F-111 and common repair techniques used to re-establish airworthiness. The highlighted area in red indicates the focus of the bonded repair program, in which the adhesive bond of the applied doubler to the existing aluminium skin is interrogated to determine condition after service exposure.*

Phase 1 testing was undertaken from the 25th of October to the 3rd of December, 2010 at RAAF Base Amberley. Phase 1 methods have been documented previously [6]. Phase 2 testing was undertaken from the 16th to the 27th of May, 2011 at RAAF Base Amberley. The test procedure was identical to that used in Phase 1. Additionally, many smaller panels that had been removed from the aircraft were sent to DSTO-Melbourne for more detailed inspections. Phase 3 testing covers all work performed at DSTO Melbourne on panels that had been removed from the aircraft. Phase 3 testing commenced in May 2011 and at the date of publication of this report is still underway.

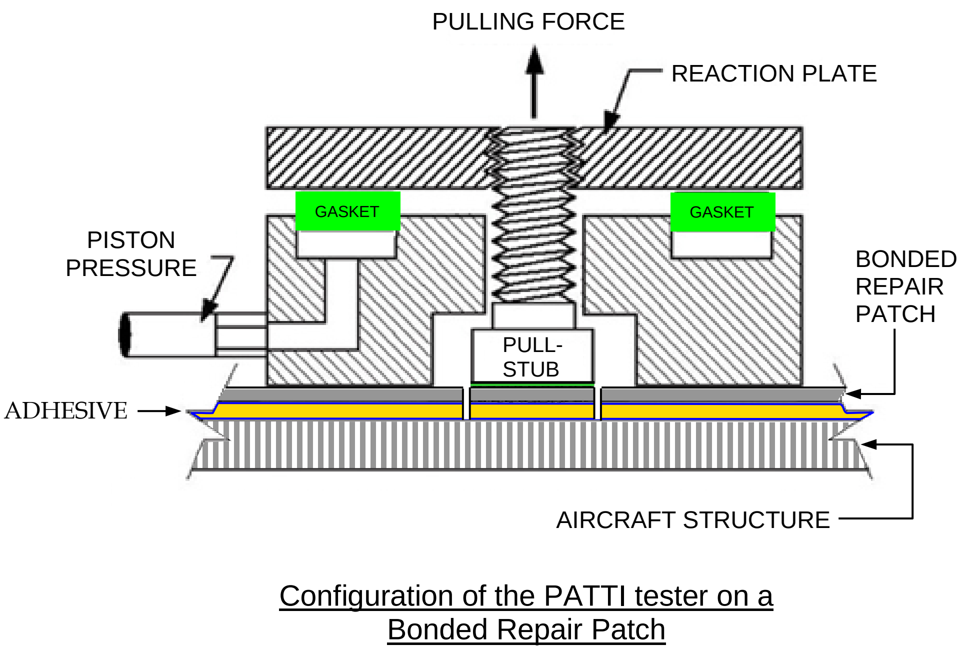

Figure 2 *Pneumatic Adhesion Tensile Testing Instrument (PATTI) used to interrogate the residual strength of the bonded repairs on F-111 honeycomb stiffened structure*

3. Method

3.1 PATTI Testing of Adhesively Bonded Repairs

The test method used in Phase 2 was very similar to that used in Phase 1, and summarised below. The method is explained in more detail in reference 6.

1. Identify potential repairs to be tested. Remove sealant from the edge of repair, and verify that the adhesive corresponds to a DEFAUST9005 compliant repair.

2. Where possible, perform non-destructive inspection (NDI) on repairs.

3. Photograph repairs, showing any NDI indications.

4. Determine regions for portable adhesion testing using the Pneumatic Adhesion Tensile Testing Instrument (PATTI).

5. Route out the doubler test area for each stub used in the PATTI test.

6. Clean and abrade area for testing then bond on test stubs using EA9309.3NA paste adhesive.

7. Perform PATTI® testing with Elcometer 110 PATTI® to measure flatwise-tension strength of the bond

8. Photograph failure surfaces and place the stubs in sealed, labelled bags

9. Remove doubler using a wedge and pliers or multigrips

10. Photograph repair failure surfaces and place doublers in a sealed, labelled plastic bags.

The test method used in Phase 3 is identical to that described above, except that the NDI techniques included radiography, ultrasonic A-scan, and a technique such as Bondmaster, as well as tap testing. The completed tests have been included in this publication, and any further results will be reported in a future publication.

4. Results and Discussion

4.1 PATTI Testing of F-111 Adhesively Bonded Repairs

The majority of repairs inspected during FABRAP were manufactured using Cytec FM300 or Cytec FM300-2K structural film adhesive. A few inspected repairs used Cytec FM73 structural film adhesive, or a grey paste adhesive that was most likely Hysol EA934. Because of the small numbers of FM73 and EA934 repairs, they have been excluded from

the data set as the population is statistically insignificant and the processes applied using these adhesives is not known with confidence. This report examines FM300-2K in detail, with FM300 repairs examined in a previous report [4]. A total of 217 PATTI stubs from 73 repairs were inspected during FABRAP that had been applied using FM300-2K adhesive, and after extraneous data points had been removed (the process of data removal is described later in the report), 70 repairs were assessed as suitable for use in analysis. Figure 3 shows the distribution of repair strengths of the 70 repairs. The repair strength is assessed on the basis of the average pull-off tension strength measured using the PATTI test for each repair. The average strength may involve between one and more than ten pull-off tests on a given repair. The number of tests conducted per repair was heavily dependent on the repair size. Consequently, smaller repairs may only have a single pull-off test and tend to distort the overall results, particularly, in cases where high curvature angles could make a single test quite variable. In the previous work examining FM300 repairs, a decision was made to exclude results where a repair measurement was based on only a single test conducted on a repair, due to statistical uncertainty that could unreasonably skew the overall trend in data. Removal of the FM300-2K repairs with only a single test conducted reduces the number of repairs to 50.

Figure 3 shows the strength distribution of the 50 bonded repairs which had two or more tests, alongside the 70 repairs which include those with a single test. The overall distribution in strength of the repairs with greater than two tests is similar to the total population set, and the average strengths of the full data set and reduced data set were similar, at 14.4 MPa and 14.7 MPa, respectively.

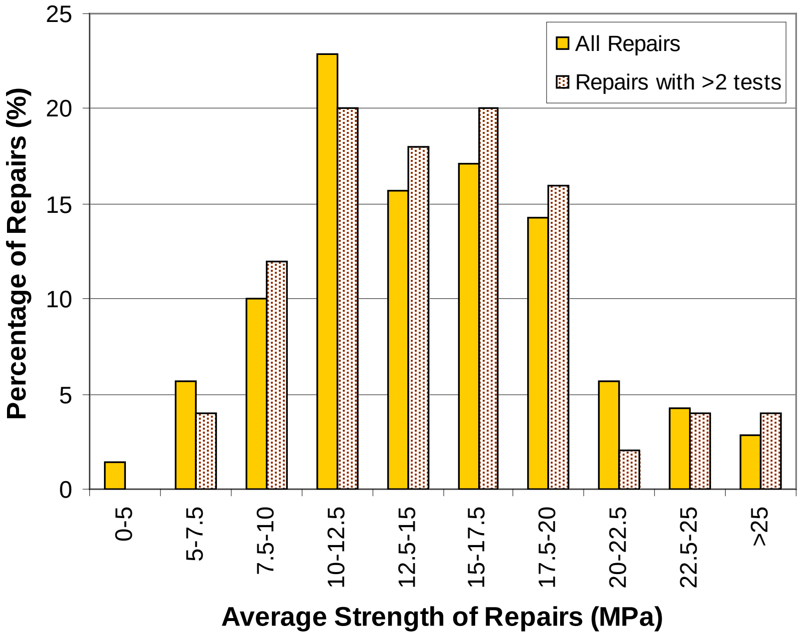

Figure 3 The distribution of repair strength for the 70 FM300-2K repairs tested during the bonded repair trial, and the 50 repairs for which there were two or more tests

If repairs with no traceable service history are also excluded, the dataset is further reduced to only 25 repairs, with strength distribution shown in Figure 4. However a dataset of 25 may be too small to give meaningful results. Based on the previous study [4], which found that service history, based on either total accumulated time or total number of flight hours since repair application, had no discernible influence on repair strength, it was also decided to keep all the repairs for further analysis, not just those with a traceable service history.

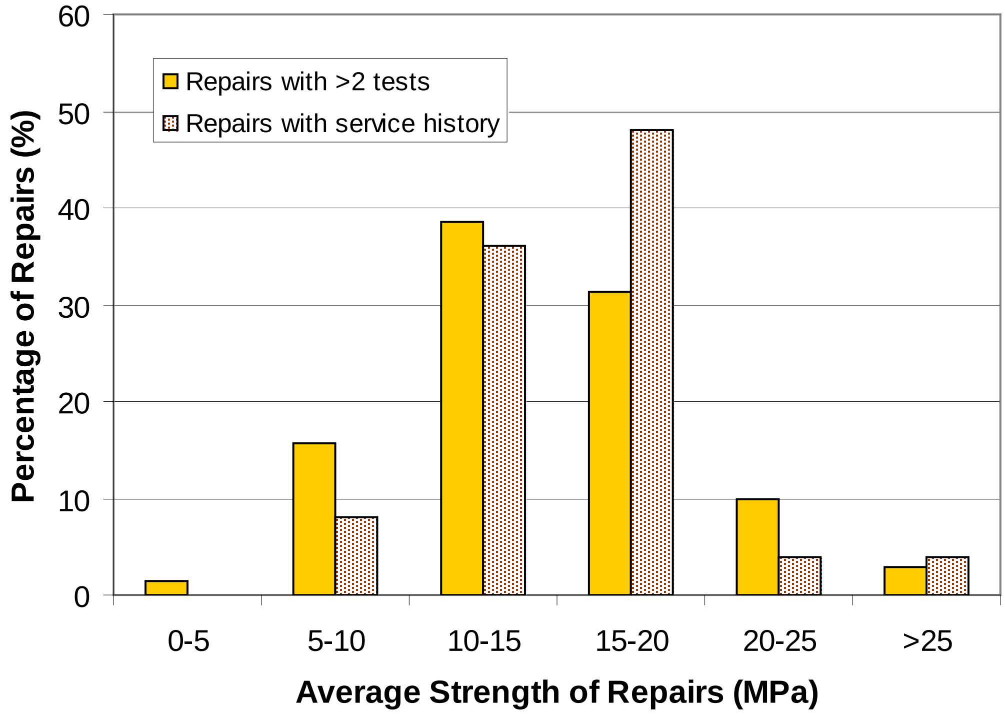

Figure 4 *The distribution of strength of the 25 FM300-2K repairs in which records detailing the repair application processes, dates of application and service history are available, compared with the larger data set of 50 repairs with two or more tests. The reduced data set may not be representative of the larger data set.*

The benefit of the current testing method, in which the PATTI stubs were specifically located as close to the edge of the doubler as possible, also provides a method which helps to remove any effects that repair size may have on the analysis. By placing the stubs at the doubler edges, the bondline area being interrogated should experience similar environmental conditions, irrespective of the overall repair size. The test location also examines the area of the doubler that would have experienced the greatest environmental exposure and, therefore, provides a measure of the maximum effect that moisture and the environment may have had on the bond strength. It should be noted that the moisture only has access to the bondline from the edges of the repair either through the adhesive layer or the adhesive/aluminium interfaces or both.

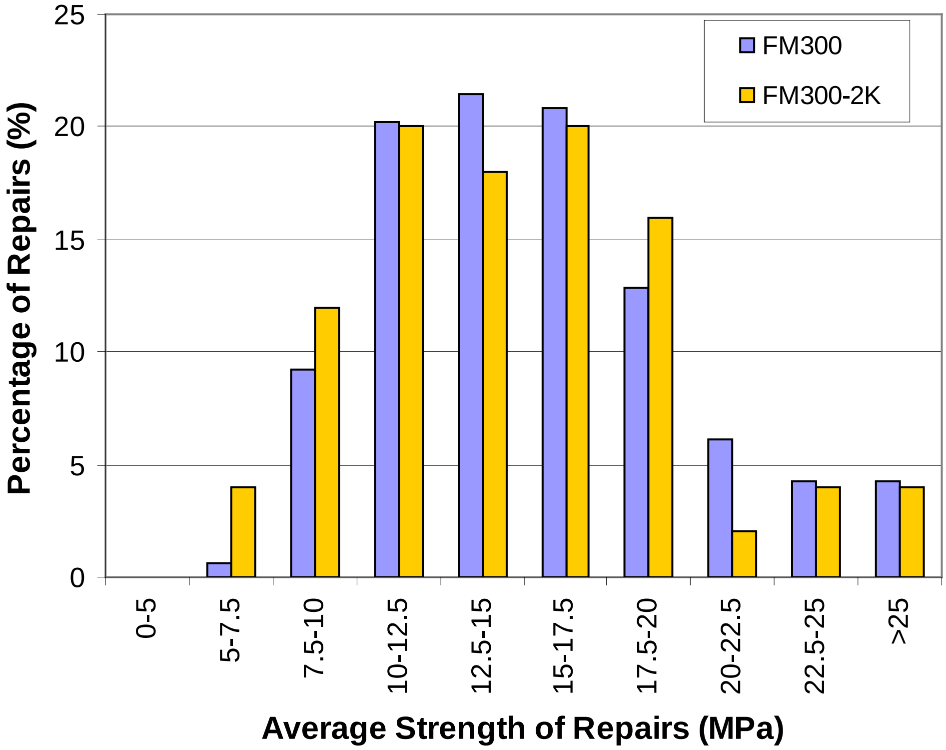

Figure 5 The distribution of repair strength for the 163 FM300 and 50 FM300-2K repairs tested during the bonded repair trial, for which there were two or more tests

The strength distribution of FM300 and FM300-2K repairs with two or more tests is compared in Figure 5 above. The average (mean) FM300 repair strength is 15.4 MPa, compared with 14.7 MPa for FM300-2K repairs, and the median repair strength is 14.8 MPa for both FM300 and FM300-2K repairs.

4.1.1 The Effect of Repair Age and Service History

One of the hurdles to certification of bonded repairs is accurately quantifying the effect of age on the repair strength. Water compromises the bond chemistry as there is a thermodynamic driving force for individual water molecules to displace the adhesive bonds from the metallic substrate once the moisture has diffused through the adhesive bondline or along the interphase region. After extended exposure to a hot and humid environment, there is potential for the bond strength to be degraded if surface treatments and application of the adhesive bond have not been carried out correctly. Currently, there are no available non-destructive inspection techniques to establish if the bond strength has degraded due to in-service exposure. Additionally, the strength of a recently applied bonded repair is unknown and, therefore, the reliability of the technology is also questioned. Consequently, the only way to prove the reliability and environmental resistance of a bonded repair is to destructively assess its condition after application and

service. The assessment of the bonded repairs has used a combination of in-situ mechanical tests, which provide a semi-quantitative measure of the bond strength in localised regions, combined with a visual assessment of the doubler and skin surfaces, post-doubler removal. Extensive efforts were also made to correlate the inspected repairs with service history, to provide a measure of repair condition with both accumulated flight hours and total life-time of environmental exposure.

Where possible, the repairs investigated during the adhesive bond inspection program were matched with the repair paperwork completed by the bond shop at the time of repair application, although in some cases they were only matched with the paperwork that specified the design of the repair. The repair paperwork helps to date the repair, and where an engineering design existed, but there was no bond-shop paperwork, it was assumed that the repair was undertaken within two months of the design approval (evidence suggests that this is an acceptable assumption). The repair paperwork would often include information on the repair environment, such as temperature, humidity, and time taken to perform each process, which can also affect the quality of the adhesive bond. Due to resourcing constraints this progress report does not investigate the effect of the repair environment during application on the measured repair-strength, however, this is an area for future reporting.

Once the repairs were dated, many could be matched up with aircraft service histories. This is important as some components were easily interchangeable between aircraft, and when a component was removed for repair, it did not necessarily go back on the same aircraft. Sometimes repaired panels or components would be spare and stored until needed.

The initial analysis of the bonded repairs examined if a correlation existed with the average repair strength and the repair age (Figure 6). The repair age represents the total accumulated time since the repair was applied to the time the repair was tested. There is no correlation in strength with repair age as indicated by the wide distributions of strength that exist for the repairs ranging between 500 and 5100 days or around 1.5 to 14 years. The extent of variation for discrete repair ages is greater than the difference in the average value for nearly all the data. Two repairs, A8-112-22 and A8-512-05 fall below the expected lower limit. These will be examined in further detail in Section 4.1.2.

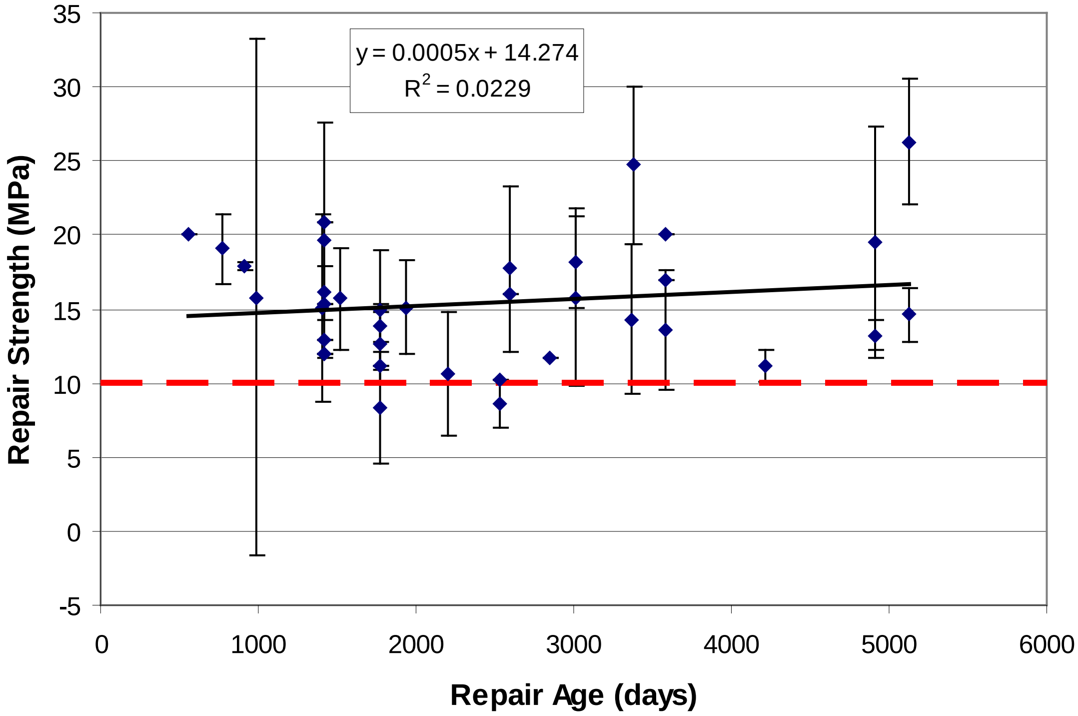

Figure 6 The repair strength measured as a function of total age of the repair where the error bars represent the 95% confidence interval. The broken red line represents the lower limit expected for undegraded bonds accounting for possible geometrical variations in loading.

Figure 7 indicates the average repair strength as a function of accumulated flight hours. The data is similar to Figure 6 and shows that the strength does not depend on the accumulated flight hours, with the variation of repair strength at discrete times being typically greater than the average strength over a period between 100 and 1600 hours. The two repairs that fall below the expected lower limit are the same as those in Figure 6.

The results from both Figure 6 and Figure 7 suggest that, it is equally likely that a repair randomly measured for strength over a period of at least 5000 days of total life or 2100 hours flight time or both will have an average strength around 15.8 MPa with a 95% confidence interval around ±2 MPa. These initial results show that with 95% confidence, a minimum strength around 13 MPa would be expected for the total lifetime of the repairs examined. This is above the 10 MPa lower limit which was nominated for repairs manufactured using FM300 film adhesive, when accounting for variation in bondline strength that would simply be due to geometrical loading effects, discussed in the previous report [6]. However the strength of two repairs fall below 10 MPa, and further analysis of these repairs is undertaken in the following section.

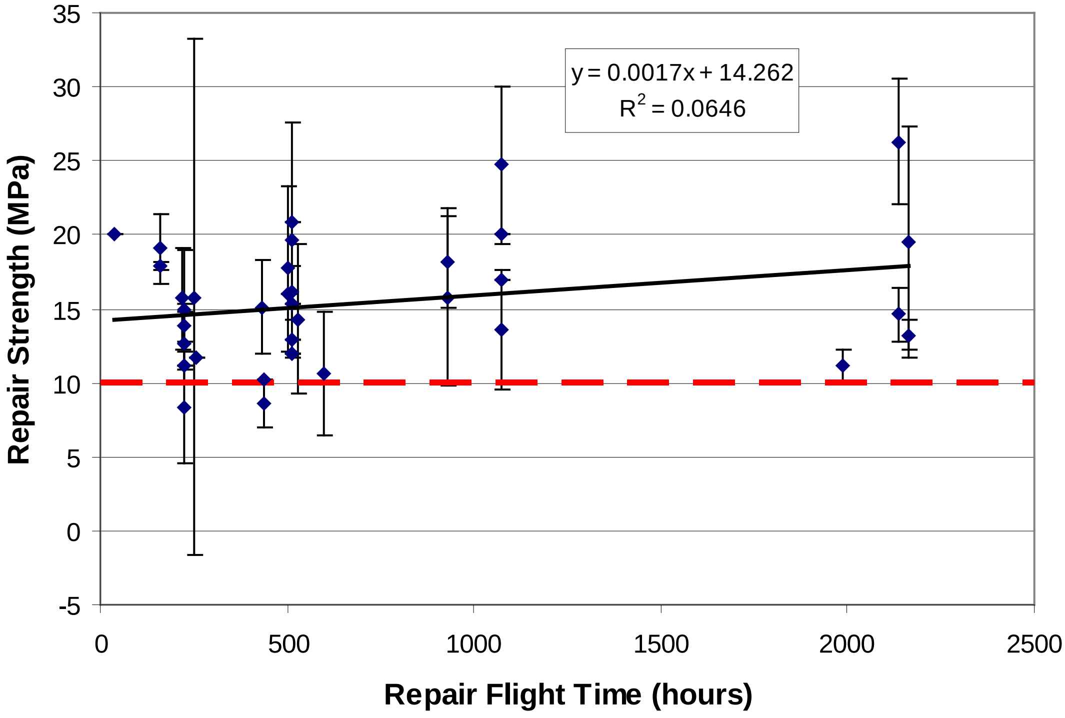

Figure 7 *Correlation between flight hours experienced by each repair and average repair strength, where the error bars represent the 95% confidence interval for all repairs measured with the same accumulated flight hours. The broken red line represents the lower limit expected for undegraded bonds accounting for possible geometrical variations in loading. Single data point repairs have been excluded.*

4.1.2 Further Data Interrogation

In the previous section, two low strength repairs were noted, A8-112-22 and A8-512-05. These were examined more closely with details shown in Table 1. Although there were explanations for the low stub strengths, it was decided that these represented situations that, although uncommon, would be encountered in real world bonding and testing applications.

Table 1 Details of low strength repairs in Figure 6 and Figure 7

Stub ID	Stub Strength (MPa)	Explanation for Anomaly	Decision	Reason
A8-112-22A	11.0	No anomaly	Keep	
A8-112-22B	5.6	Operators reported stub failed in peel mode instead of pull-off tension	Keep	Although severe peel failure was uncommon, this is indicative of normal variations in the test due to geometry/testing conditions
A8-512-05A	7.4	Very thick adhesive layer toward one side of stub – inconsistent bondline can cause loading variations	Keep	Representative of potential bondline inconsistencies in real repairs
A8-512-05B	9.8	No obvious explanation	Keep	

Further analysis examined whether any other anomalies existed which warranted investigation. Five data points could be excluded from the data set under investigation. These data points are described in more detail in Table 2. Originally there were 72 inspected FM300-2K repairs, but after exclusion of these five data points, 70 repairs remained.

Table 2 Details of individual test stub result examinations and reasons for excluding the measured PATTI strength from the overall dataset

Repair Stub ID	Explanation for Anomaly	Decision	Reason
A8-114-03A	Stub bonded over rivet.	Remove from dataset	Not representative of adhesive to aluminium bond prepared by standard methods
A8-131-33A	Stub bonded over the core insert instead of skin-to-doubler region.	Remove from dataset	Not representative of adhesive to aluminium bond prepared by standard methods
A8-131-34A	Stub bonded over a filled hole instead of skin-to-doubler region.	Remove from dataset	Not representative of adhesive to aluminium bond prepared by standard methods
A8-512-02E	Test stub located on top of old rivet. Adhesive is well bonded to rivet head, but low strength likely caused by a pre-existing failure in the rivet shank. This is one example where the presence of a bonded repair would have made other routine inspections difficult.	Remove from dataset	Not representative of adhesive to aluminium bond prepared by standard methods
DSTO-03-03B	Stub bonded over the core insert instead of skin-to-doubler region.	Remove from dataset	Not representative of adhesive to aluminium bond prepared by standard methods

After the individual test stubs detailed in Table 2 were excluded, repairs with only one stub were also removed from the data set, as one data point per repair does not provide a significant statistical distribution. However this reduced the data set of FM300-2K repairs to only 50, so it was decided to reinstate single data point repairs for the purposes of investigations into low strength stubs. Figure 8 shows the distribution of average repair strength in the modified data set for each aircraft or from specific components for which DSTO had recovered the paperwork, denoted as DSTO-03 and DSTO-10. It can be seen that A8-114, A8-271 and DSTO-03 have repairs where the spread in strength, which is represented by the 95% confidence limit error bars, drops below the 10 MPa limit.

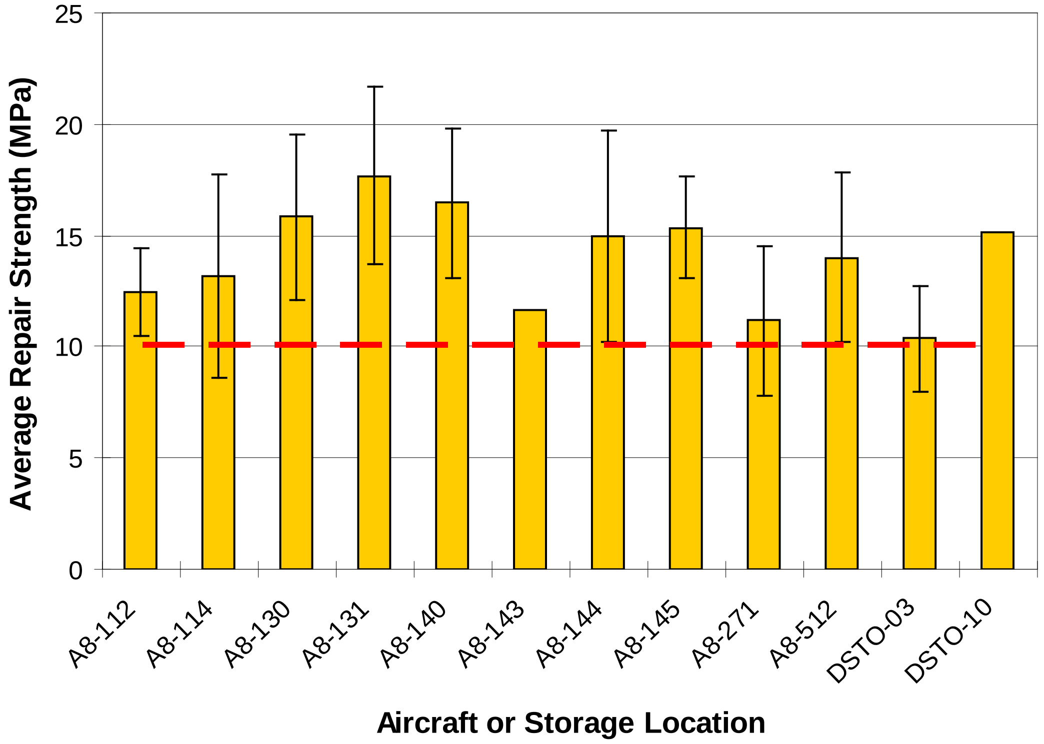

Figure 8 *Average repair strength for each aircraft examined or for components recovered from storage locations. The dataset has stub results reported in Table 2 removed. The broken red line represents the lower limit expected for undegraded bonds accounting for possible geometrical variations in loading.*

Specifically, repairs number three, four and five from A8-114 had ten pull stub tests carried out between them and eight of the ten tests had strengths below 10 MPa. On Aircraft A8-271, all three stubs on repair 5 had strengths lower than 10 MPa. On repair 13, all three stubs had strengths below 10 MPa, as well as all three stubs on repair 14, and two of the three stubs on repair 18. Where the repair strength average of all stubs dropped below 10 MPa, the individual stubs were examined in further detail, shown in Table 3. It

was noted that most low strength stubs exhibited high levels of adhesion failure and high levels of residual abrasion debris, which will be discussed further in Section 5.3. However, as discussed later, many high strength stubs also exhibited adhesion failure and abrasion debris, so this was not considered a suitable explanation for the low strength. What appears to be adhesion failure may be the "normal" failure mode for brittle adhesives, and may simply be an indication that FM300-2K is more brittle than FM300. Only repair A8-114-03 had a possible explanation for the low strength, that is, poor preparation of the surface prior to bonding, and possibly poor application of vacuum pressure during curing, which may have led to poor wetting. These shortfalls may in part be explained, but not expected, by the difficult location, as the repairs were on the lower surface of a horizontal stabiliser, a component that is normally repaired in-situ as it is too bulky and heavy to be easily moved into the ideal environment and position for repairs.

Note that component DSTO-03 is a special case as it was a vane. Repairs to vanes were commonly required due to impact damage caused by insufficient clearance of the aircraft rigging. It was fairly common for these repairs to be damaged and re-repaired, and non-destructive inspections prior to testing suggested that there may have been delamination damage on one of the inspected repairs. The curved surfaces of vanes may additionally cause decreased measured stub strengths due to misalignment of the piston. This component will be examined in more detail in a future report focussing on the non-destructive inspection of adhesively bonded repairs examined during FABRAP.

Table 3 Details of repairs from aircraft A8-114 and A8-271, which showed consistently low pull-stub strengths

Repair No.	Stub ID	Stub Strength (MPa)	Failure Surface Stub	Failure Surface Repair	Repair Environment/Age
A8-114 – 03 Repair on lower surface of left horizontal stabiliser, which may have caused difficulties in surface preparation and application of repair	03A	6.2	Stub on top of a rivet – do not include	Very uneven appearance, shiny strip across repair suggests insufficient grit blast, long stringer voids suggest inadequate drying before bonding, poor contact between adhesive and aircraft structure/repair	Application environment unknown. Accumulated hours and flight history unknown
	03B	4.5	Insufficient grit blast, possible uneven silane application, possible poor wetting, adhesion failure		
	03C	11.8	Insufficient grit blast, abrasion debris present[1], adhesion failure		
	03F	9.8	Insufficient grit blast, possible poor wetting, adhesion failure		
	03G	7.6	Possible uneven silane application, poor wetting, adhesion failure		
A8-114 – 04 Repair on lower surface of left	04A	9.8	Mostly adhesion failure, abrasion debris present	Large voids between core cutouts suggest inadequate	Application environment unknown.
	04B	10.3	Adhesion failure, abrasion debris present		

[1] The presence of abrasion debris on the adhesive failure surface is discussed in detail in Section 5.1

Repair No.	Stub ID	Stub Strength (MPa)	Failure Surface Stub	Failure Surface Repair	Repair Environment/Age
horizontal stabiliser	04D	8.6	Adhesion failure, abrasion debris present	drying and volatile removal before bonding, and areas where adhesive wetting appears poor.	Accumulated hours and flight history unknown
	04E	9.3	Mostly adhesion failure, abrasion debris present		
A8-271 – 05 Repair on upper surface of right horizontal stabiliser	05A	8.6	Adhesion failure, abrasion debris present, insufficient grit blast	Doubler not removed	Application environment unknown. Accumulated hours and flight history unknown
	05B	9.0	Adhesion failure, abrasion debris present, insufficient grit blast		
	05C	6.1	Operators reported possible peel failure, abrasion debris present		
A8-271 – 13 Panel 3423	13A	5.7	Adhesion failure, abrasion debris present, small hole in substrate – could be an injection repair?	Doubler not removed	Application environment unknown. Accumulated hours and flight history unknown
	13B	7.4	Adhesion failure, abrasion debris present, small hole in substrate – could be an injection repair?		
	13C	5.6	Adhesion failure, abrasion debris present		
A8-271 – 14 Panel 3423	14A	5.0	Adhesion failure, abrasion debris present, pink adhesive in bond line (from bonding on stub) indicates this area was not bonded prior to test (failure surface suggests may have been poor contact). Small hole in substrate – could be an injection repair?	Doubler not removed	Application environment unknown. Accumulated hours and flight history unknown
	14B	5.4	Failure surface indicates delamination in the area closest to a fastener, difficult to confirm as substrate not available for inspection		
	14C	5.5	Adhesion failure, abrasion debris present, some voiding		

Figure 9 shows the average repair strength as a function of total repair age for the modified dataset where individual stub results from Table 2 were removed from the original dataset, as well as any repairs where only a single adhesion stub was tested. The results show that the average repair strength across the 15 years is around 15.8 MPa with a standard deviation of 4.2 MPa and 95% confidence interval around ±2 MPa. The lack of correlation between repair age and strength provides an encouraging indication that the strength of the bonded repairs does not appear to be affected over a considerable period of time. Generally, the spread in data appears to be relatively consistent over the period of the analysis, which suggests that the variability in strength measurements is inherent in

the intrinsic strength of the repairs, as applied, as well as the measurement techniques used. It should also be noted that the data filtering applied has reduced the original dataset from 70 to 50 repairs, and then of those repairs only 25 had recorded application dates, but given the similar trends observed for both FM300 [4] and FM300-2K, there is some confidence that the overall analysis is representative of a larger dataset.

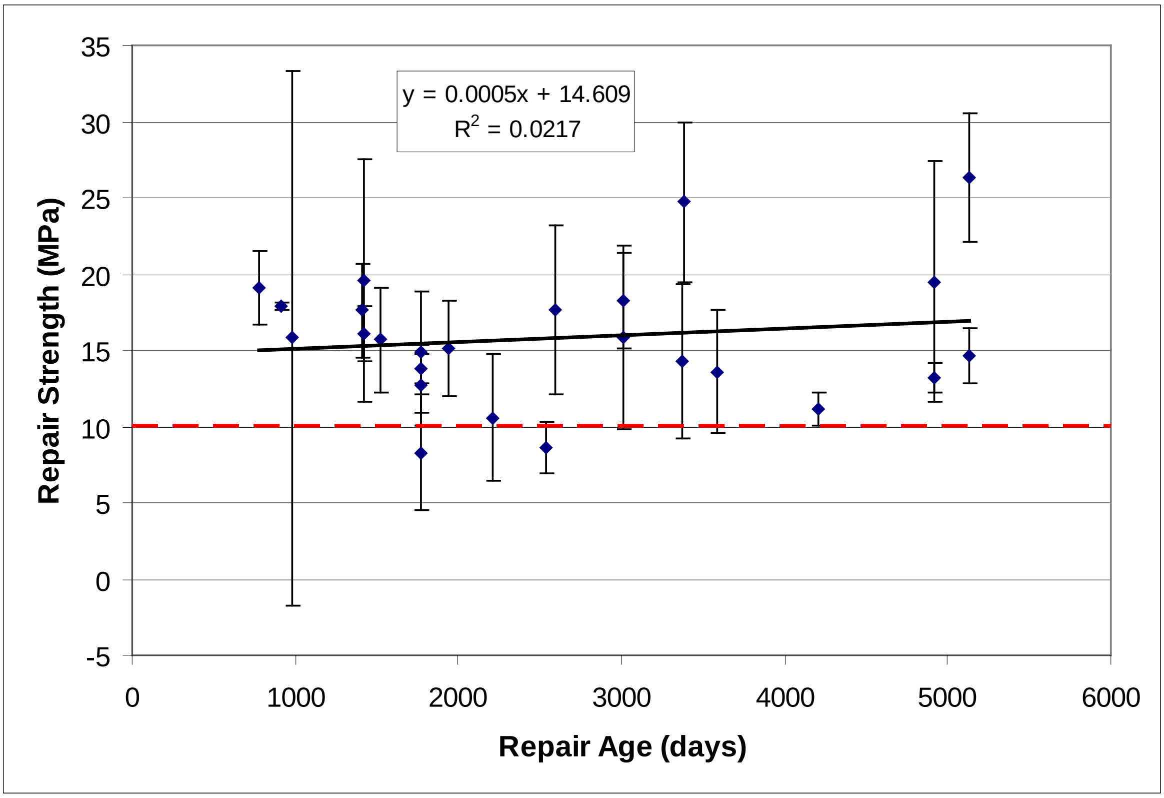

Figure 9 *The average repair strength as a function of total accumulated time since application, where individual stub results from Table 2 were removed as well as repairs where only a single stub was tested. The broken red line represents the lower limit expected for undegraded bonds accounting for possible geometrical variations in loading.*

Further analysis of the dataset in Figure 9 examined the trend in repairs where the flight hours were confidently known through a review of available paperwork, and this is shown in Figure 10. This reduced the number of repairs to 24. However, it can be seen that the trend in Figure 10 is similar to Figure 9 and Figure 7, with average repair strengths across the 2100 flight hours of data having similar average values and similar confidence limits. The average strength is 15.7 MPa with a standard deviation of 4.3 MPa and 95% confidence interval around ±2 MPa.

The two repairs in Figure 9 and Figure 10 with strengths below 10 MPa are the same as in Figure 6 and Figure 7, outlined in Table 1 and examined at the beginning of this section. The two repairs with low strength had very low flight hours, and the lack of correlation

between flight hours and repair strength provides confidence that flight hours have minimal effect on the strength of the bonded repairs. Similarly, strength variation is relatively similar for the range of times examined, suggesting the variation is inherent in the repairs and measurement techniques used. The two low strength repairs presented anomalous causes of failure, in one case, where the bondline was uneven causing variations in loading, and in the other case, there was an operator comment that the test stub was known to have failed in peel rather than pull-off tension. It appears that the lower strength results recorded for these stubs is a genuine indication of a reduced bond strength from the average, but are likely due to inadequacies associated with original application or test configuration. There were no signs of degradation associated with moisture absorption in the bondline or along the interphase.

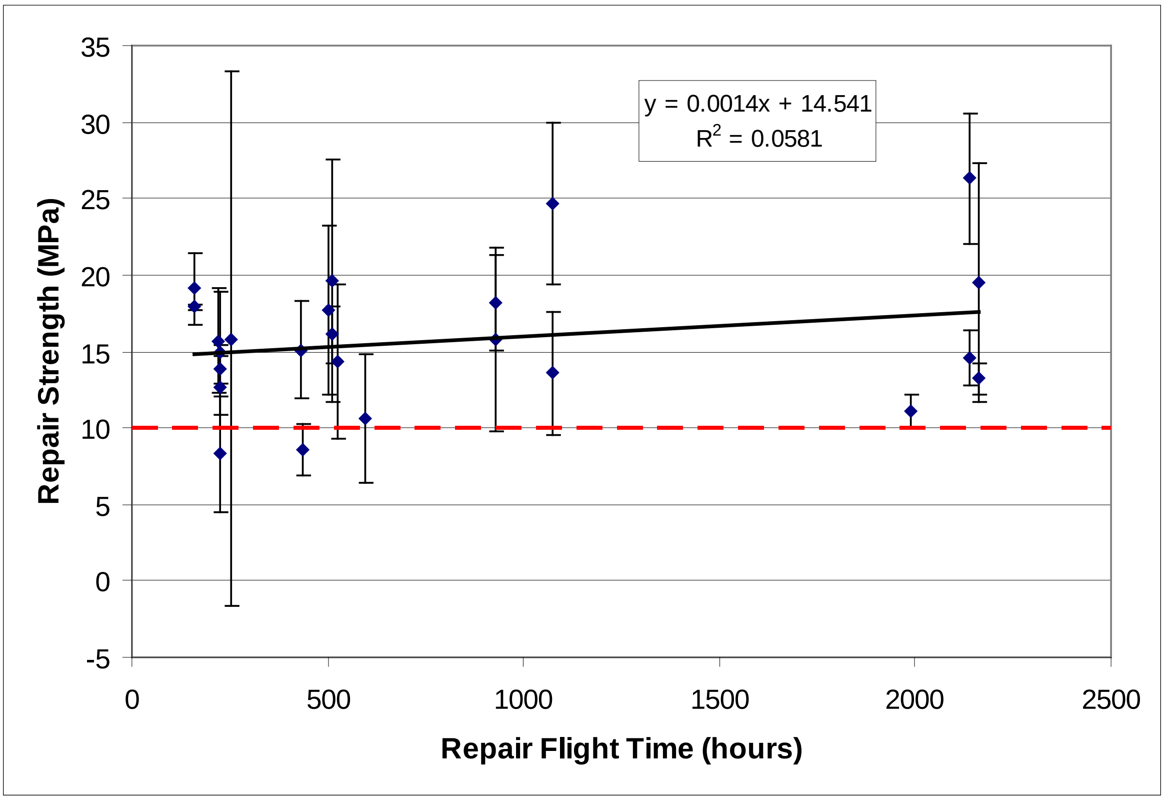

Figure 10 Only repairs with a traceable service history have been included in this data set. This reduced the number of repairs to 24.

4.1.3 Detailed Analysis of Low Strength Pull Stubs

As indicated in the statistical analysis above, the average bonded repair strength in a single repair may overlook the case where low individual stub strengths exist when the overall repair strength is satisfactory. Consequently, all cases in the filtered data shown in Figure 8 were examined where stub strengths were below 10 MPa. In addition to those already shown in Table 3, Table 4 shows results for individual stub results used to calculate the average repair strength. The individual pull-stub strengths below 10 MPa have failure causes detailed.

The reasons for the reduction in strength of individual stubs can be classified into three broad areas: 1) Poor adhesive wetting, 2) Poor grit-blasting, 3) Other factors such as location and test configuration. If the results from Table 3, Table 4 and Table 5 are combined this provides a total of 31 stubs in which there were possible failure indications identified for 18 of the stubs.

Table 4 Details of individual pull-stub measurements where the average repair strength was below 10 MPa for the FM300-2K repair dataset, and anomalous results detailed in Table 2

Aircraft	Repair-Stub ID	Stub Strength (MPa)	Failure Surface Stub	Failure Surface Repair	Repair Environment /Age
A8-112	22A	11.0	OK	Some voiding, and adhesion failure around core region.	within limits/ 1772 days/ 224afhr
	22B	5.6	Operators noted that stub removal had a large peel component, which may have contributed to lower test strength. Abrasion debris evident		
A8-114	05A	6.8	Adhesion failure, some abrasion debris	Some voiding but not too bad	unknown/ unknown
A8-140	07A	4.3	Adhesion failure, abrasion debris.		
A8-271	12	See Table 5 below			
A8-512	05A	7.4	Very thick adhesive layer toward one side of stub	Doubler not removed	within limits/ 2535 days/ 437afhr
	05B	9.8			
DSTO-03	02A	7.9	On curved surface. Adhesion failure, abrasion debris. Some voiding.	Adhesion failure	unknown/ unknown
	02B	6.2	On curved surface. Adhesion failure, abrasion debris.		
	02C	11.1			
	02D	16.0	Small amount of adhesion failure.		
	03E	7.0	On curved surface, mostly adhesion failure.		unknown/ unknown

In stark contrast with the low strength FM300 repairs, many of which exhibited heavy voiding, only a few low strength stubs exhibited obvious voiding, and only one of which was identified in Table 3 and Table 4. One other repair, shown in Figure 11, exhibited heavy void tracks emanating from core repair regions, however there was no obvious voiding at the locations of the test stubs. This type of voiding is typically caused by insufficient drying of the core cut-out region after solvent cleaning. During adhesive

curing at elevated temperatures, the solvent gases expand, an effect which is heightened by the vacuum pressure applied to repairs during cure. These two repairs with voiding indications are highlighted in green in Table 3 and Table 4.

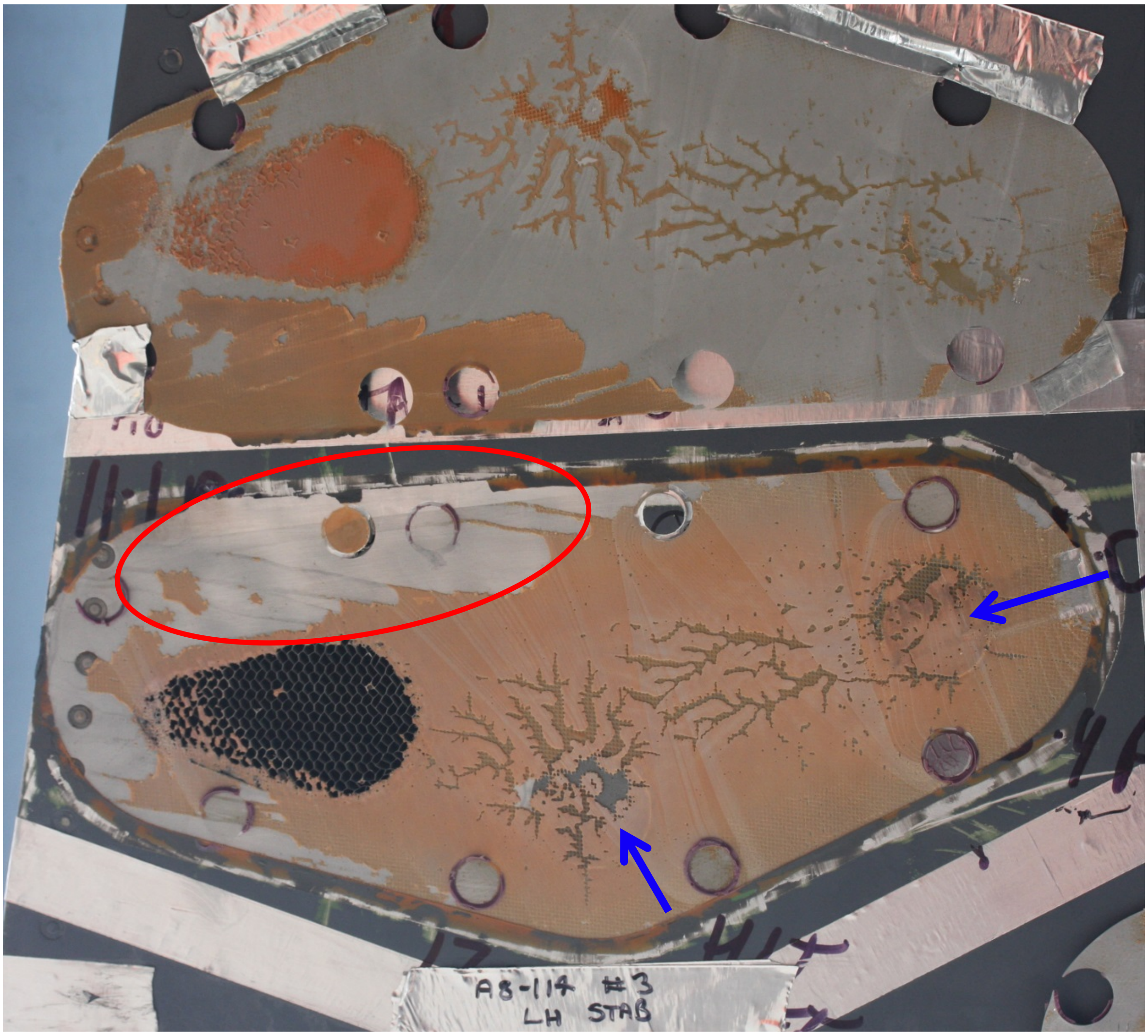

Figure 11 *Repair 114-3 shows heavy voiding emanating from some of the areas of repaired core, indicated by the blue arrows. This is characteristic of inadequate drying following cleaning. The area along the top left of the repair, encircled in red, has an uneven appearance with shiny areas indicating insufficient gritblast.*

Amongst the lowest strengths observed were stubs for which there were apparent adhesive wetting problems, highlighted in blue in Table 3. The example shown in Figure 11, in addition to heavy voiding, also appears to have had problems with wetting, most noticeably on the left side. Cases where the adhesive has not wetted either the doubler or aircraft skin are normally indicative of inadequate vacuum pressure being applied during the repair. It is more difficult to obtain good vacuum pressure close to the edge of a

component, as there are sometimes problems with vacuum bag leaks due to imperfect seals around fasteners and bags being folded around the back side of the panel. The low strength of these areas suggests that whilst it was a relatively unusual problem, poor wetting was one of the more serious problems that could affect overall repair strength.

The next category of fracture surface identified, leading to lower localised repair strength, was observed for regions where the grit-blasting coverage appeared to be inadequate, highlighted by grey in Table 3 and Table 4. Once again, the example shown in Figure 11 illustrates this deficiency, with an apparent patchy surface and shiny strip across the top, suggesting that the level of grit-blasting was inadequate. The causes of low grit-blast coverage could potentially be related to difficulties with the equipment, which has been identified previously for wedge test samples prepared at Amberley over a number of years [7]. An inspection tool, the BYK Gardner Micro TRI Gloss® gloss-meter, had previously been identified as being suitable for indicating whether aluminium surfaces have been adequately grit-blasted as part of the RAAF process for preparing adhesively bonded repairs [8]. Incorporation of this tool in pre-bond quality assurance testing would be expected to improve the quality of adhesively bonded repairs.

A few stubs highlighted in purple in Table 3 and Table 4 could be explained by various reasons that did not fall into a particular grouping, e.g. near a fastener hole which may have caused delamination due to over-tightening, or, the stub was on a curved surface, which may have caused piston misalignment/peel failure. These and other stubs with apparent cause of failure only present on one or two repairs were placed in the "other" grouping for statistical purposes.

A summary of the failure indications and the average strength associated with each type is provided in Figure 12 below. Many stubs had two or three possible failure indications, in which case the stub was counted against each category. The results indicate the average strength for each indication type, with the spread in data shown by error bars, which represent the 95% confidence limits. The plot provides a useful measure of the relative severity of each type of failure with respect to the reduction in the overall stub strength in the locally affected areas. Stubs that fell into the "other" category had the lowest strength. One stub was close to a fastener hole, and this stub is examined in detail in Section 5.2. One stub had an operator comment that the stub may have failed in the peel mode rather than pull-off tension due to test configuration, and three more were on highly curved surfaces which have a higher likelihood of being affected by peel due to piston misalignment. It is understood that a peel failure component leads to a lower measured pull-off tension strength. However, it is difficult to exclude repairs on curved surfaces as the majority of aircraft surfaces are curved. Several stubs from repair 271-12 were placed in the "other" category, as this repair showed a severe deficiency in bond preparation, which will be examined in further detail in Section 5.1.

Poor adhesive wetting of the aluminium surfaces led to significant decreases in strength, indicating identification of these defects would have the highest priority in repair inspection and maintenance. Poor grit-blasting and voiding also appear to cause a significant reduction in strength compared to the stubs with no indications, but does not appear to lead to as significant a reduction as wetting. These would be important to

identify in any post repair inspections. The areas of the repair without any indications provided average strengths higher than the average values determined in Figure 9 and Figure 10. Note, however, that less than five percent of closely examined test stubs exhibited a failure surface with no unusual failure indications. Normally adhesion failure would be considered an indicator of deficiencies in the bonding process, however roughly 80% of test stubs exhibited apparent adhesion failure, and many of these had high strength.

This suggests that average repair strengths for the filtered data represent the significant majority of the total repair areas examined. The data suggests that major degradation in strength was confined to relatively localised regions such as around fastener holes. Other causes of low strength, such as poor wetting and grit-blasting, would have been present when the repair was new. Generally, this would imply that no single repair had significant levels of strength reduction associated with long term environmental or service exposure.

Excessive voiding was originally noted as a possible cause of failure, however, as shown in Figure 12, the average strength of stubs that presented voiding was 9.5 MPa, which is only slightly lower than the nominal "pass" value of 10 MPa. The presence of excessive abrasion debris, thought to indicate poor cleaning, was originally noted as a possible cause of low failure strength, however with an average strength of 10.1 MPa and with excessive abrasion debris present on many high strength stubs, the effect on the bond strength may be minimal, as discussed in further detail in Section 5.1.

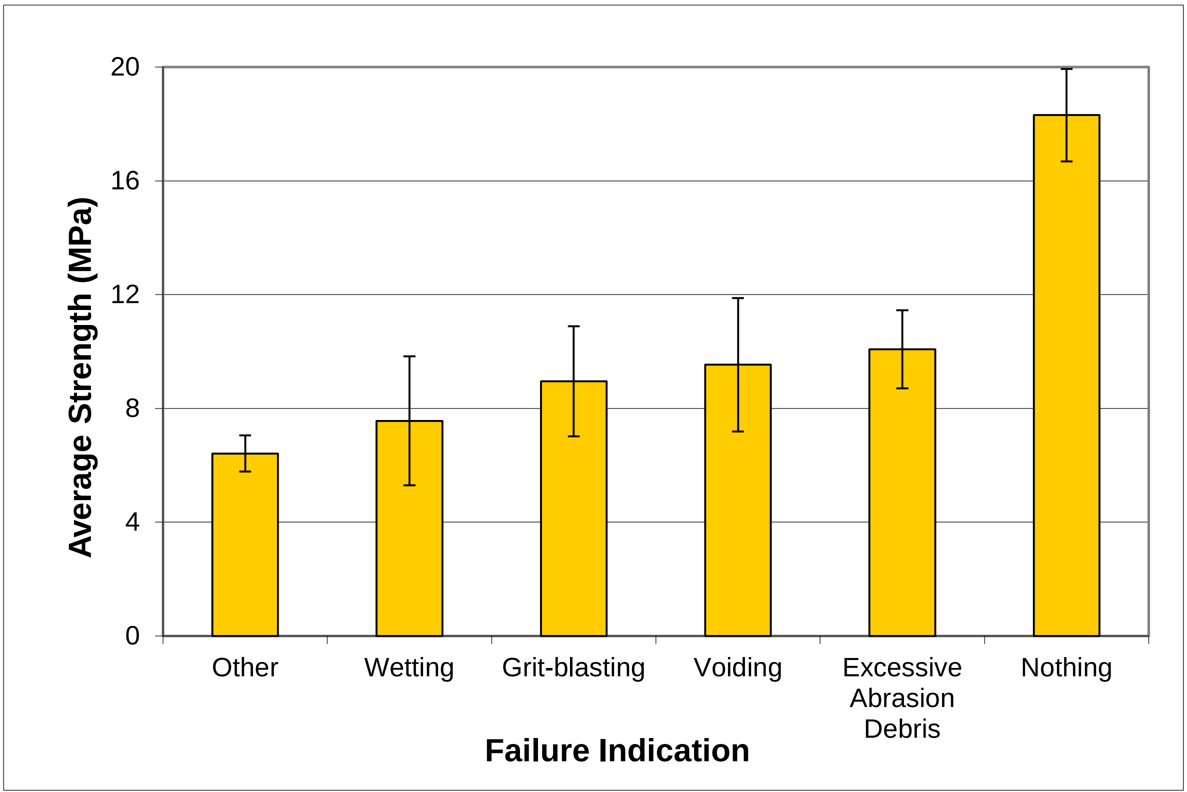

Figure 12 *Average strength for individual pull-stubs with failure indications categorised according to problems with adhesive wetting (wetting), inadequate grit-blasting (grit-blasting), high levels of voiding (voiding) adhesion failure with no identified cause (adhesion failure), and uncategorised causes (other). The strengths are compared to stubs measured on the same repairs without any indications (nothing).*

5. Failure Investigations

5.1 Insufficient Cleaning Prior to Bonding

An interesting finding was that the failure surfaces of the majority of low strength stubs exhibited one or both of two unusual features. The first feature was metallic-looking streaks that appear to follow Scotchbrite abrasion lines (refer to Figure 14); the second was a powdery white/grey appearance (refer to Figure 16). These features were only evident on the adhesion failure portion of failure surfaces. A few high strength stubs were also examined more closely, and of those that failed in adhesion (as opposed to failing cohesively), the same powdery appearance was also evident. It seemed that this failure phenomenon was fairly widespread and not confined to low-strength stubs. This led to a closer examination of FM300 test stubs, and it was discovered that of the few FM300 test stubs that exhibited adhesion failure, many also had the same powdery appearance, but it was not obvious as the white/grey powder colour blends with the blue colour of the adhesive, and not many FM300 stubs exhibited adhesion failure.

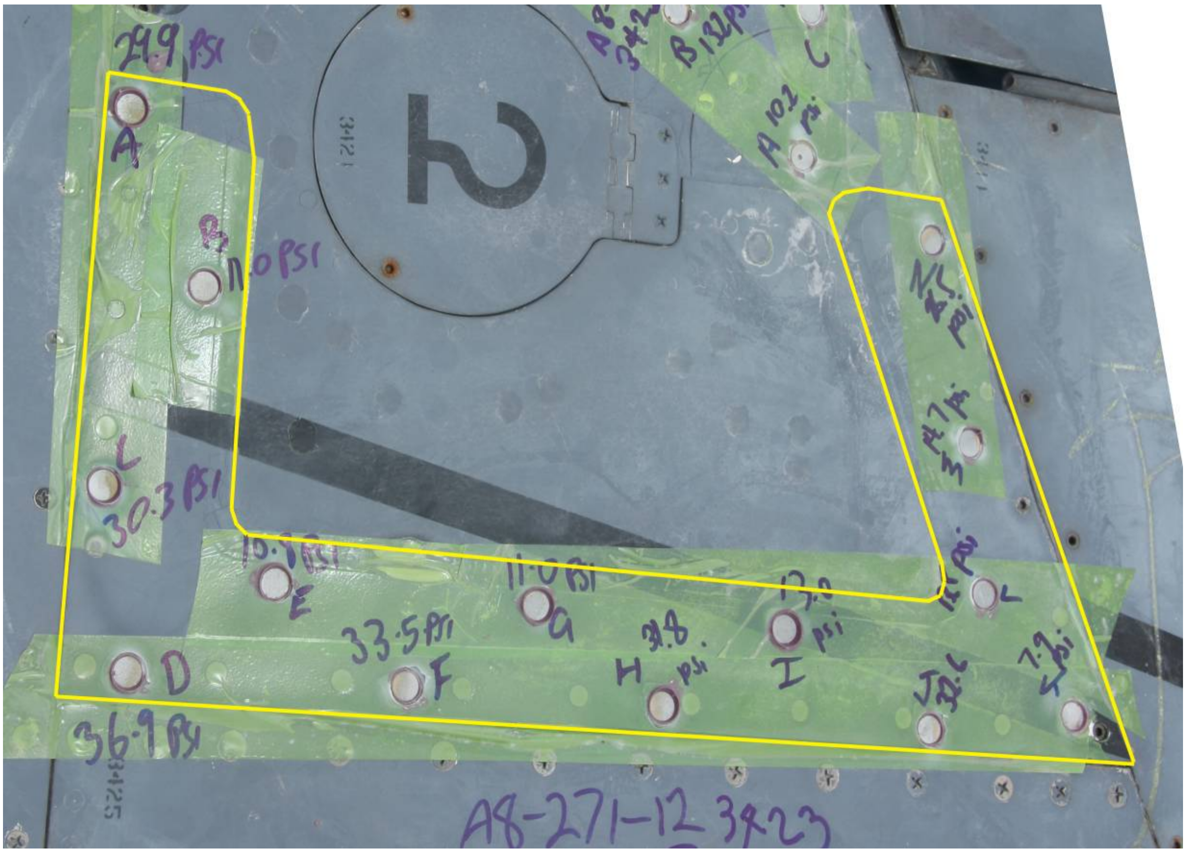

Figure 13 Repair 271-12, on aircraft A8-271, panel 3423

Repair number 271-12, made using FM300-2K, was chosen for closer inspection as a case study, as it had low and high strength stubs, and several stubs had a particularly unusual appearance. Figure 13 shows the repair, on panel 3423, outlined in yellow. Table 5 shows the strengths of the stubs on repair 271-12.

Table 5 Details of test stubs from repair A8-271-12, panel 3423

Stub ID	Burst Pressure (psig)	Pull-Off Tensile Strength (MPa)	Failure Surface Aircraft Side	Failure Surface Stub Side
12K	7.9	4.4	Signs of fluid ingress in a region that had disbonded prior to test	Largely adhesion failure, metallic abrasion lines across part of area, >50% is discoloured, suggesting fluid ingress into disbonded region
12E	10.8	6.1	Largely adhesion failure, green tape line through stub	
12B	11.0	6.2	Largely adhesion failure, green tape line through stub	Largely adhesion failure, green tape line through stub, metallic abrasion lines, some voids
12G	11.0	6.2	Largely adhesion failure, green tape line through stub	Largely adhesion failure, green tape line through stub, metallic abrasion lines, some voids
12I	13.0	7.3	Largely adhesion failure,	Largely adhesion failure, green tape

			green tape line through stub	line through stub, abrasion debris, several voids
12L	13.5	7.6	Largely adhesion failure, green tape line through stub	Largely adhesion failure, green tape line through stub, metallic abrasion lines and debris visible
12M	14.7	8.2	Largely adhesion failure	Largely adhesion failure, metallic abrasion lines and debris visible
12N	26.5	14.9	Largely adhesion failure, green tape line through stub	
12A	29.9	16.8	Some adhesion failure towards edge of repair	
12C	30.3	17.0	70% adhesion failure towards edge of repair	
12H	31.8	17.9	Mostly cohesive failure	
12J	32.6	18.3		70% adhesion failure, some voids, on top of a rivet, abrasion debris
12F	33.5	18.8	>50% adhesion failure	70% adhesion failure
12D	36.9	20.7		60% adhesion failure, some voids, on top of a rivet, metallic abrasion lines

On closer examination of the failure surfaces, stubs B, E, G, I, L and N all appeared to have a line running across them. Figure 14a and Figure 14b show in greater detail the failure surfaces of 271-12B stub and aircraft side, respectively, which are typical of all of the abovementioned stubs. The line appears to be a greenish colour. High temperature “flashbreaker” tape is commonly used for many purposes in bonded repair operations, and one of these purposes is to mark out an area for cleaning. The green tape in Figure 13 and Figure 14b is the same high temperature tape – note that it is the same colour as the line across stub 271-12B, shown in Figure 14b. When the tape is removed from a surface a small amount of adhesive residue from the edge of the tape is sometimes left behind.

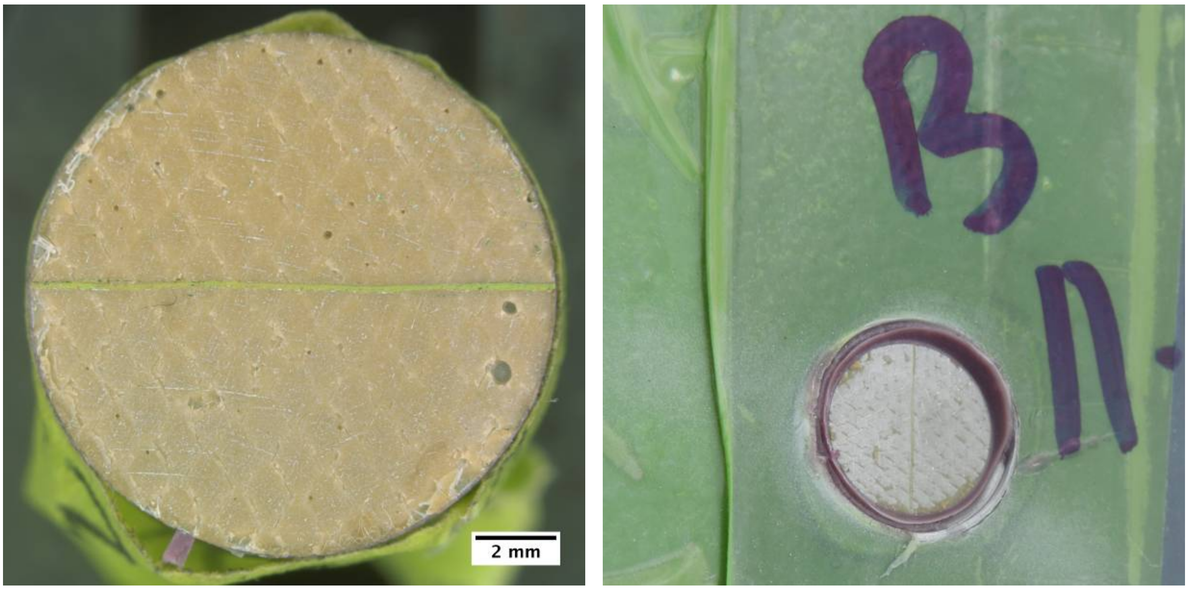

Figure 14 Failure surfaces were from low strength test stub 271-12B, showing the a) stub side, and b) aircraft side.

When all these green tape residue lines are marked out, as annotated in red on the photograph of the repair in Figure 15, it becomes apparent that the repair area had been marked out for cleaning, but that at some stage it was decided to enlarge the repair area. It appears that the additional repair area was not cleaned as thoroughly as necessary, as the green tape line should have been easily removed by wiping with a solvent-dampened tissue. If the enlarged repair area was not cleaned properly, it would explain why the above-mentioned stubs all had a lower measured strength than the other stubs on the same repair.

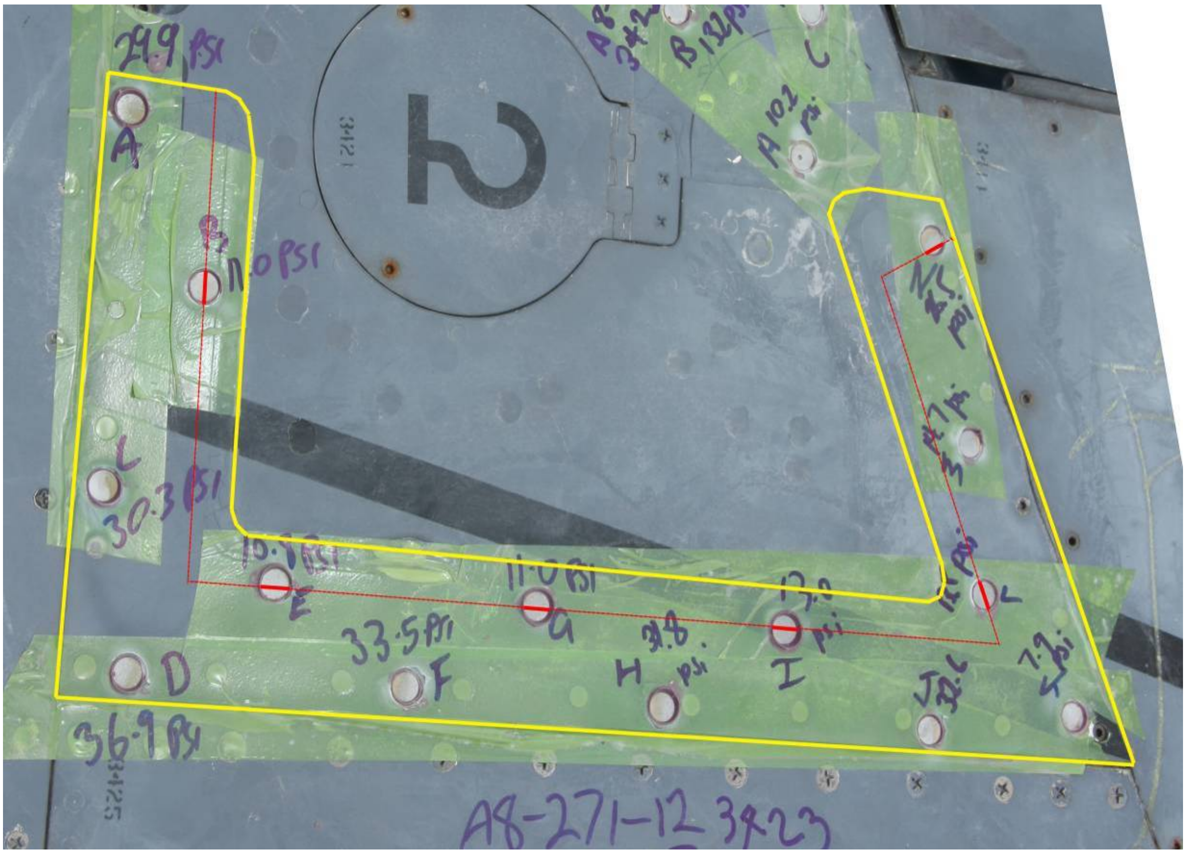

Figure 15 Repair 271-12, on aircraft A8-271, panel 3423, with tape residues annotated in red

The failure surfaces of the test stubs were examined using optical microscopy. Two of the failure surfaces were also examined by energy dispersive x-ray spectroscopy (EDS) on a JEOL scanning electron microscope, using a beam energy level of 5kV.

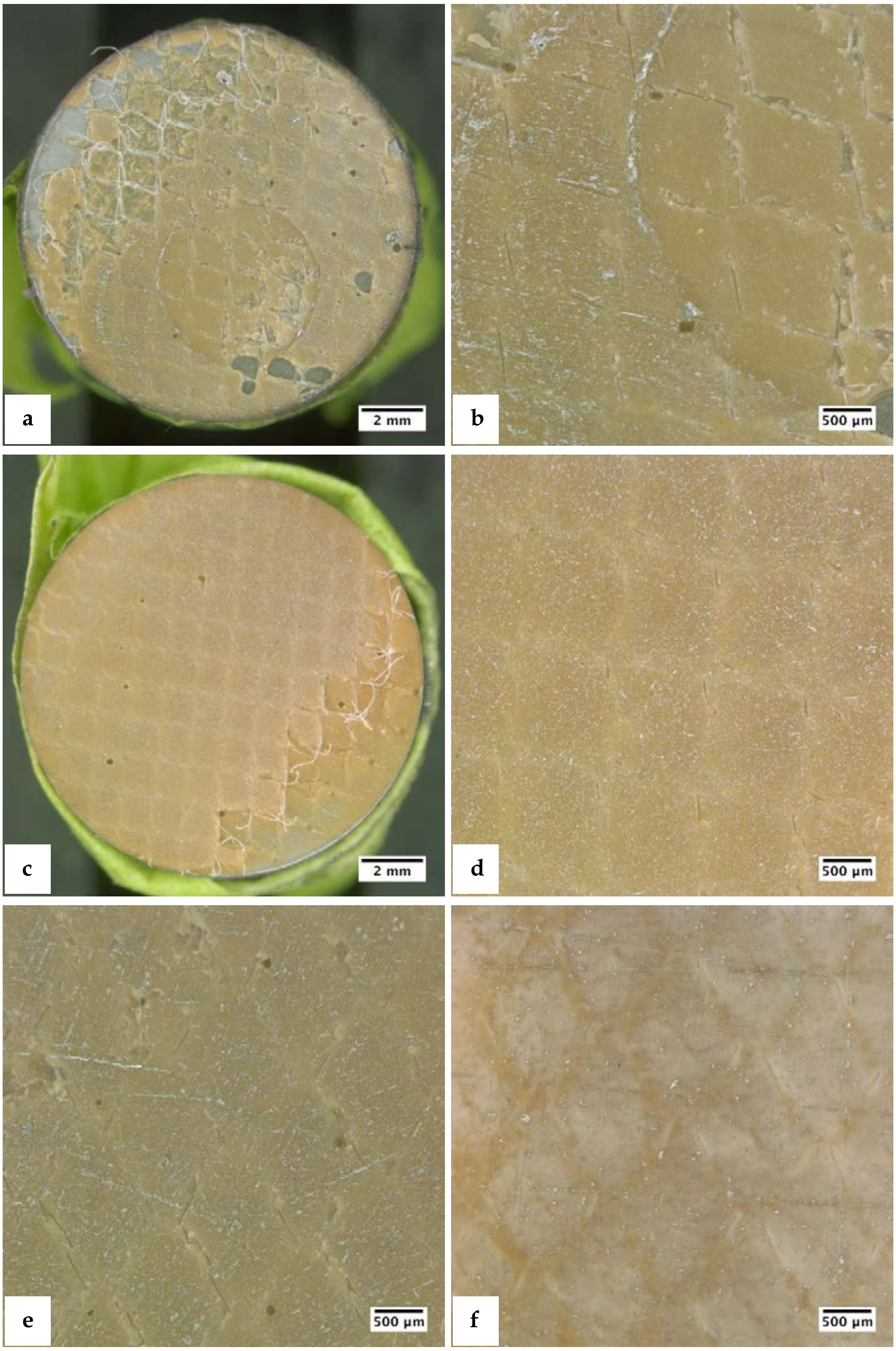

Figure 16a) & b) Failure surface of stub 271-12J, which had high strength
c) & d) Failure surface of stub 140-07A, which had low strength
e) Failure surface of stub 271-12B, which had low strength
f) Failure surface of a requalification wedge test

When stub 271-12B was examined in more detail (Figure 16e), it became evident that the metallic powder and lines are debris left over from the Scotchbrite abrasion step of the cleaning process. By comparison, stub 271-12J (Figure 16a and b) was a high strength stub, incidentally located over a rivet. The area bonded to the rivet head appears quite clean, with much less abrasion debris. The partial rings of debris on one side of the rivet suggest that the rivet was in place during cleaning, and the debris collected around the edge of the rivet. Later cleaning may have dislodged some of the debris, but did not completely remove it. The rivet may have had a higher hardness than the aircraft skin, which would make it more difficult to abrade, leaving less debris on the rivet head.

The elemental content of the failure surfaces measured by EDS confirm that the regions that appear covered in aluminium debris do indeed contain higher levels of aluminium on the surfaces, compared to the regions that appear cleaner. These results are shown in Table 6. The individual EDS spectra are included for reference in Appendix A: .

Table 6 Elemental content of failure surfaces measured by EDS

Test Stub	Description	Carbon	Oxygen	Aluminium
271-12J	Spectrum 16 clean region	76.0	18.4	5.6
	Spectrum 17 clean region	75.4	18.0	6.6
	Spectrum 20 dirty region	62.8	15.1	22.1
	Spectrum 21 dirty region	59.8	14.0	26.2

The spectra can be taken using an area scan or a point scan. As the specimens are a non-conductive adhesive and were not coated with a conducting film, there was excessive electron charging and image drift due to the electrons being unable to make a clear conductive path to ground. This meant that clear scanning electron images were not able to be taken, and caused the point scans to be slightly inaccurate in their locations. To avoid this problem, area scans were taken of test stub 271-12J, giving an average elemental composition of the total area. As shown in Table 6, areas which appeared to have metallic debris gave a higher aluminium indication in the EDS spectra than the rivet location in which metallic debris was less pronounced. This supports the theory that the metallic appearance is caused by aluminium debris left over after Scotchbrite abrasion. In fact, where the lines are evident, they are often curved in a manner that suggests a powered abrasive wheel with Scotchbrite disc was used for the abrasion step. The use of the abrasive wheel is acceptable, but the amount of debris left behind is not. A wedge test specimen sent to DSTO for technician requalification purposes was examined as reference.

Technicians who are required to perform bonded repairs on aircraft are currently required to be certified and requalified on an annual basis to the standards set out in AAP 7021.016-2 [3] and DEF(AUST) 9005 [1]. The certification and requalification tool is called the Wedge Test. Full details of the materials used, surface preparation procedure, and adhesive cure conditions are recorded. Assessors watch the process carefully and make notes on whether or not each step was undertaken in a satisfactory manner. The wedge test is representative of best practice, while aircraft repairs may be performed in non-optimal conditions. This particular specimen, shown in Figure 14, had failed unusually in adhesion. The cause of adhesion failure was thought to have been due to an error in measuring the silane

coupling agent (which may have resulted in insufficient silane coupling agent at the interface), rather than inadequate cleaning. While the failure surface still contains a small amount of aluminium debris, it is clear that the quantity of debris is dramatically less than on test stubs 271-12F, 271-12J and 140-7A. This suggests that bonded repairs of lower quality may occasionally be produced, simply through minor deviations from the specified processes due to individual operators.

Interestingly, despite several stubs exhibiting poor cleaning and poor strength, the average repair strength of stubs presenting excessive abrasion debris was at least 10.1 MPa. Based on the previous study [4], this suggests that some procedural variations may affect the initial bond strength but this does not necessarily increase the bond's susceptibility to environmental degradation.

5.2 Delamination Around a Fastener

Another stub on repair 271-12K had one of the lowest strengths of all FM300-2K stubs inspected. This one was also examined more closely. Figure 17a and b show the aircraft side and stub side of the failure surfaces, respectively. Both sides appear to exhibit some contamination on parts of the failure surface. Focussing on the stub side, there is clear discolouration of the adhesive. The discolouration may have been caused by oxidation due to exposure to the atmosphere, or more likely, contact with fluid. The colour variation suggests that there were five distinct areas, corresponding to four different exposure events. These five areas are outlined for clarity in Figure 17c. It appears that a delamination may have begun in area 1, then progressed across areas 2, 3 and 4, before the stub finally failed in area 5 due to the PATTI inspection. The delamination may have originated from the fastener hole, and was probably caused and exacerbated by fastening/unfastening operations, however it is possible that there was some contamination of the surface in this area prior to bonding that may have contributed to low initial strength in the localised area, especially as fastener holes are likely to have grease contamination and are difficult to clean. It is unfortunate that the repair doubler was not removed, as the failure surfaces would have revealed more about the mode and cause of failure. Note that the delamination is over a very localised area and would have been discovered by non-destructive inspections before growing to a significant size.

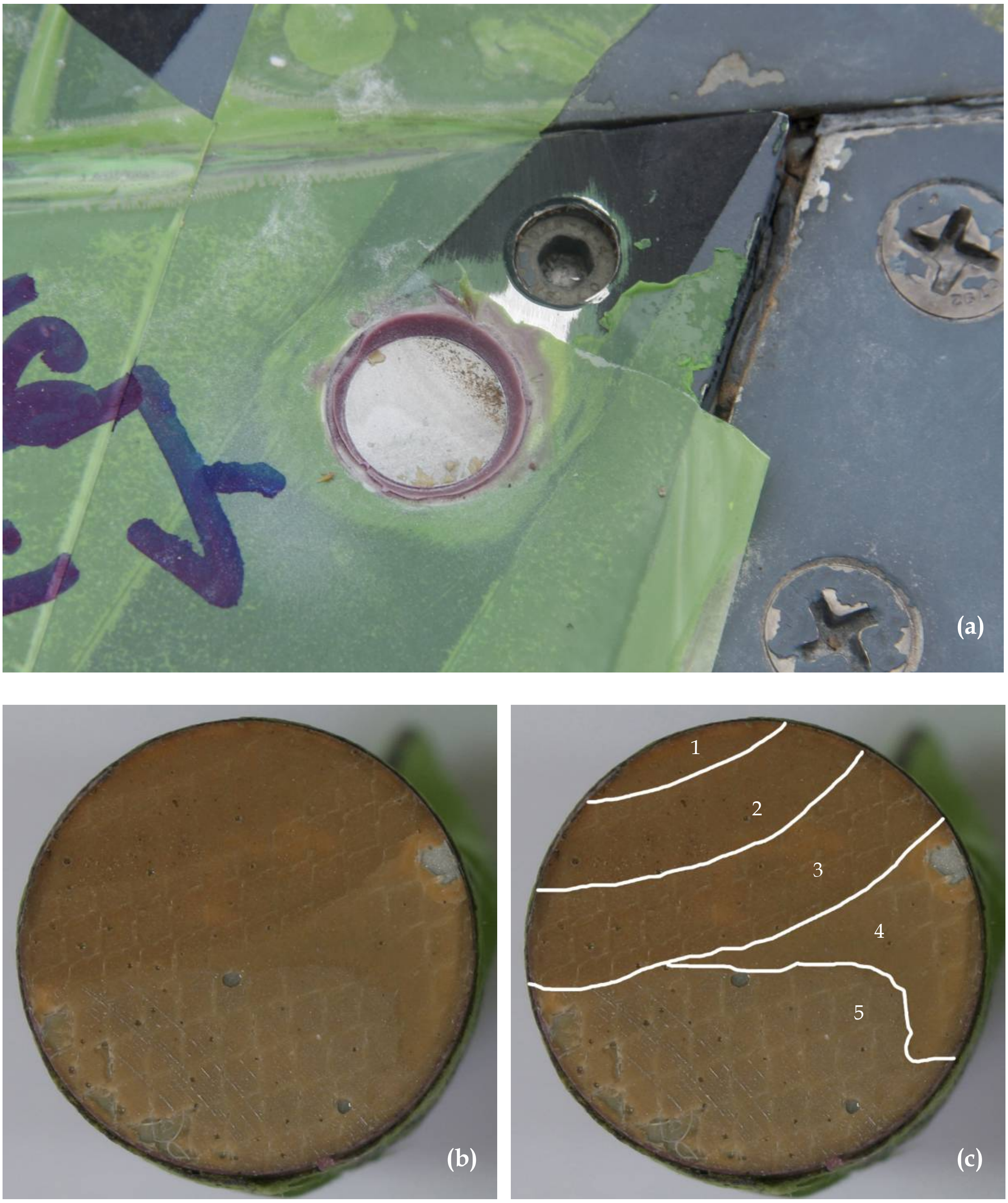

Figure 17 *The failure surfaces of test A8-271-12K, showing, (a) the aircraft side, (b) the stub side, and, (c) the stub side with apparent delamination progression zones marked.*

5.3 Comparison of Failure Surfaces

Although the average strength and strength distribution of the FM300-2K repairs was similar to the FM300 repairs, there is a marked contrast in the appearance of the failure surfaces. The majority of FM300 repairs exhibited cohesion failure, whereas the majority of FM300-2K repairs exhibit adhesion failure.

DSTO's examination of this adhesive in wedge test qualification has shown that FM300-2K appears to fail in adhesion at a much greater rate than FM300. This is thought to be due to the differences in the adhesive chemistry and curing temperature, with FM300-2K being more brittle than FM300, and FM300 seemingly more forgiving of non-optimum bonding conditions, possibly facilitated by the higher curing temperatures.

It is also known that FM300-2K is supposed to be staged before use in vacuum-assisted repairs, i.e. the adhesive film is heated to remove volatiles such as solvents or water vapour before being used to bond a repair. However this requirement had not been captured in AAP7201.016-2, which outlines the procedures to be followed in preparation of a bonded repair, and it is known that adhesive staging is not currently being performed. Almost all on-aircraft repairs are cured under vacuum. Excessive volatiles on the bonding surfaces or in the adhesive during curing under vacuum will result in the volatiles being expanded by the vacuum. The FM300 failure surfaces almost all exhibited some level of voiding, but voiding is not so obvious in most of the FM300-2K failure surfaces. A typical FM300 failure surface is shown in Figure 18a, which contrasts with the FM300-2K failure surfaces shown in Figure 16 and Figure 17. Note that the majority of FM300-2K specimens failed at the adhesive/aluminium interface, whereas the FM300 specimens mostly failed cohesively (through the adhesive, away from the interface). Figure 18b shows one of the few FM300 failure surfaces that exhibited adhesion failure, and on closer inspection, silvery lines are visible (as discussed for FM300-2K in Figure 14), but not as easily noticed as the silver blends with the blue colour of the adhesive.

Figure 18 Test stubs A8-143-5J and A8-512-22A

6. Conclusion

The following conclusions can be drawn from the analysis of the bonded repairs carried out on F-111 honeycomb structure using FM300-2K adhesive using the PATTI test to assess residual bond strength:

1) Based on an assessment of the available data from the field testing of repairs, combined with laboratory trials, it was determined that a full strength repair should normally exceed 10 MPa in pull-off tensile strength.
2) The PATTI test has provided a reliable method for screening a large number of adhesive bonded repairs conducted on the F-111 honeycomb panels over more than 15 years and generally could identify cases where repair strength was reduced relative to average baseline strength.
3) When the PATTI test results were filtered for erroneous results, it was clear that the bond strength of repairs was not affected by either service life or total accumulated hours since application.
4) The range in repair strengths across more than 15 years of life was relatively similar, which is indicative of variability associated with the repair application process or the strength measurement methods employed.
5) The trend in repair strength with repair age suggests that over a 15 year period there will be an average strength close to 15.8 MPa with a 95% confidence limit of ±2 MPa. This is very similar to the values determined for repairs with more than 2100 accumulated flight hours and similar to FM300 repairs.
6) An examination of low strength stubs, which represented localised regions of degraded repair strength, identified two general causes, poor adhesive wetting, and inadequate grit-blasting, as well as miscellaneous other causes. Poor adhesive wetting led to the most significant reductions in bond strength.
7) The analysis of FM300-2K adhesively bonded repairs conducted on F-111 honeycomb panels suggests that repairs have been applied reliably over a number of years, leading to good strength bonds with limited evidence of long term degradation associated with environmental exposure experienced during storage or flight.
8) The current results provide additional confidence in the RAAF methods that were used to apply the adhesively bonded repairs to aluminium structures when trained technicians applied the repairs in fit-for-purpose facilities.

7. Recommendations

Based on the analysis of the patches examined using the PATTI test, combined with failure surface examination, the following recommendations are provided:

1) Efforts to incorporate prebond quality assurance should be examined to ensure processes such as uniform grit-blasting are carried out adequately, given there are

signs that poor grit-blast coverage has led to areas of lower strength on some repairs.

2) Given poor adhesive wetting was identified as one of the most detrimental causes of low adhesion strength, efforts to develop reliable NDI procedures for post-bond inspection would be beneficial for the development of the bonded repair technology to primary aircraft structure. Techniques which interrogate the bond interphase region such as laser shearography [9] or laser bond inspection testing [10] may be suitable candidates. A laser bond test inspection unit has just been delivered to Boeing from LSP Technologies, indicating this technology is planned for implementation by major aircraft manufacturing companies. It is advisable that a watching brief is maintained on this technology as it has the potential to solve many of the certification problems currently faced by bonded repair technology to primary or fracture-critical aircraft structure.

8. Acknowledgements

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Appendix A: Energy Dispersive Spectroscopy

As discussed in Section 5.1, energy dispersive x-ray spectroscopy (EDS) was performed on two specimens to determine the elemental content of the failure surfaces. The elemental content of the failure surfaces measured by EDS confirm that the regions that appear covered in aluminium debris do indeed contain higher levels of aluminium on the surfaces, compared to the regions that appear cleaner. These results are shown in Table A1.

Area scans take spectra within a defined area, while point scans take spectra at specific locations. However as the specimens are a non-conductive adhesive and were not coated with a conducting film, there was excessive electron charging and image drift due to the electrons being unable to make a clear conductive path to ground. This caused the point scans to be slightly inaccurate in their locations. In test stub 271-12B, spectra 8 and 10 attempted to target specific locations where metallic streaks were visible, however it can be seen that this was not quite successful, with a wide range of readings. Spectrum 8 contained no aluminium, while spectrum 10 contained a very high level of aluminium. It is likely that spectrum 8 was actually directed at a relatively clean location just next to a metallic streak. The area scans gave an averaged reading over a larger area, hence area spectrum 1 detected a significant amount of aluminium, but at a much lower level than point spectrum 10.

To minimise the errors caused by image drift, only area scans were taken of test stub 271-12J, Areas which appeared to have metallic debris gave a higher aluminium indication in the EDS spectra than the rivet location in which metallic debris was less pronounced. The spectra and locations where they were taken are shown in Figures A1 to A6. This supports the theory that the metallic appearance is caused by aluminium debris left over after Scotchbrite abrasion.

Table A 1 Elemental content of failure surfaces measured by EDS

Test Stub	Description	Carbon	Oxygen	Aluminium
271-12B	Spectrum 1 low strength stub (area)	73.8	17.8	8.5
	Spectrum 8 low strength stub (point)	84.6	15.4	-
	Spectrum 10 low strength stub (point)	51.5	10.7	37.8
271-12J	Spectrum 16 clean region (area)	76.0	18.4	5.6
	Spectrum 17 clean region (area)	75.4	18.0	6.6
	Spectrum 20 dirty region (area)	62.8	15.1	22.1
	Spectrum 21 dirty region (area)	59.8	14.0	26.2

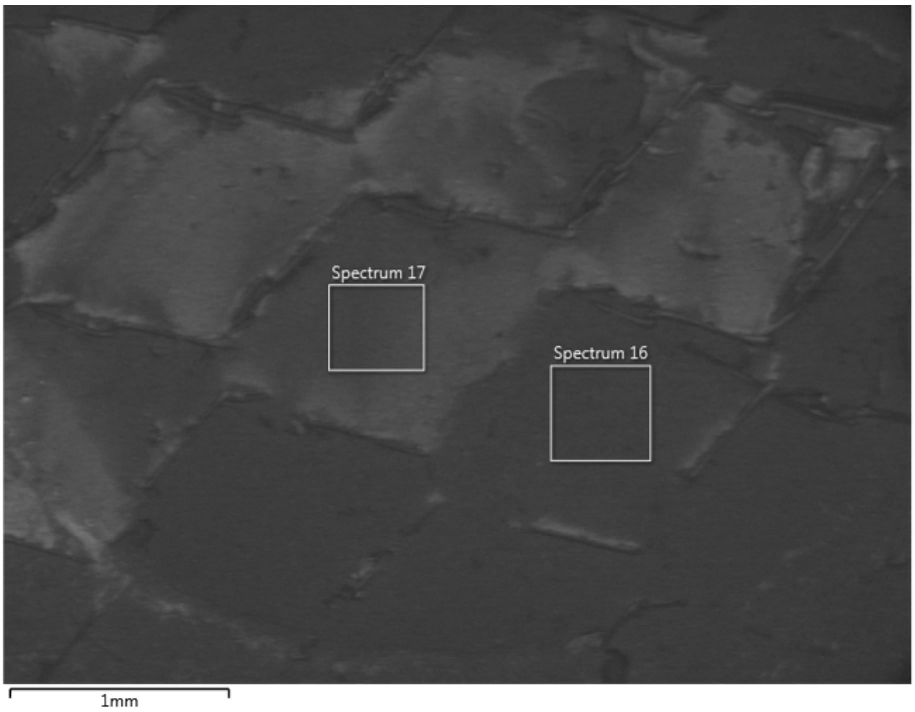

Figure A 1 Spectra 16 and 17 were taken on the surface matching the rivet head location

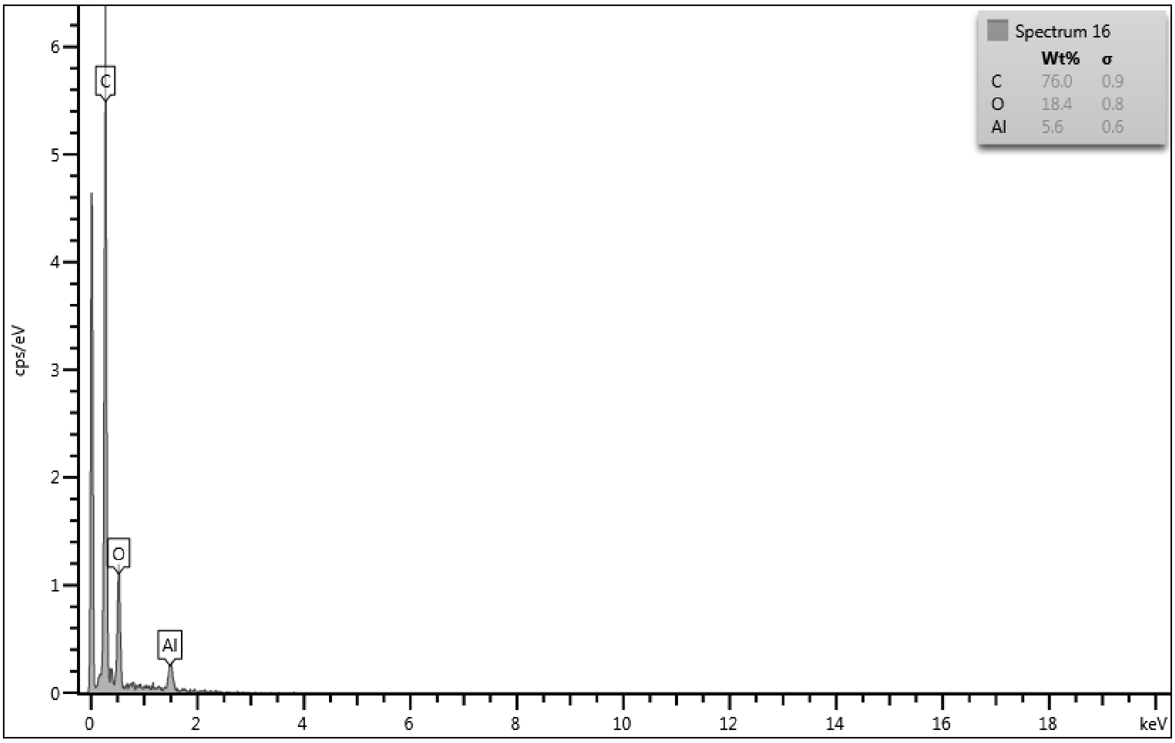

Figure A 2 Spectrum 16 was taken on the surface matching the rivet head location

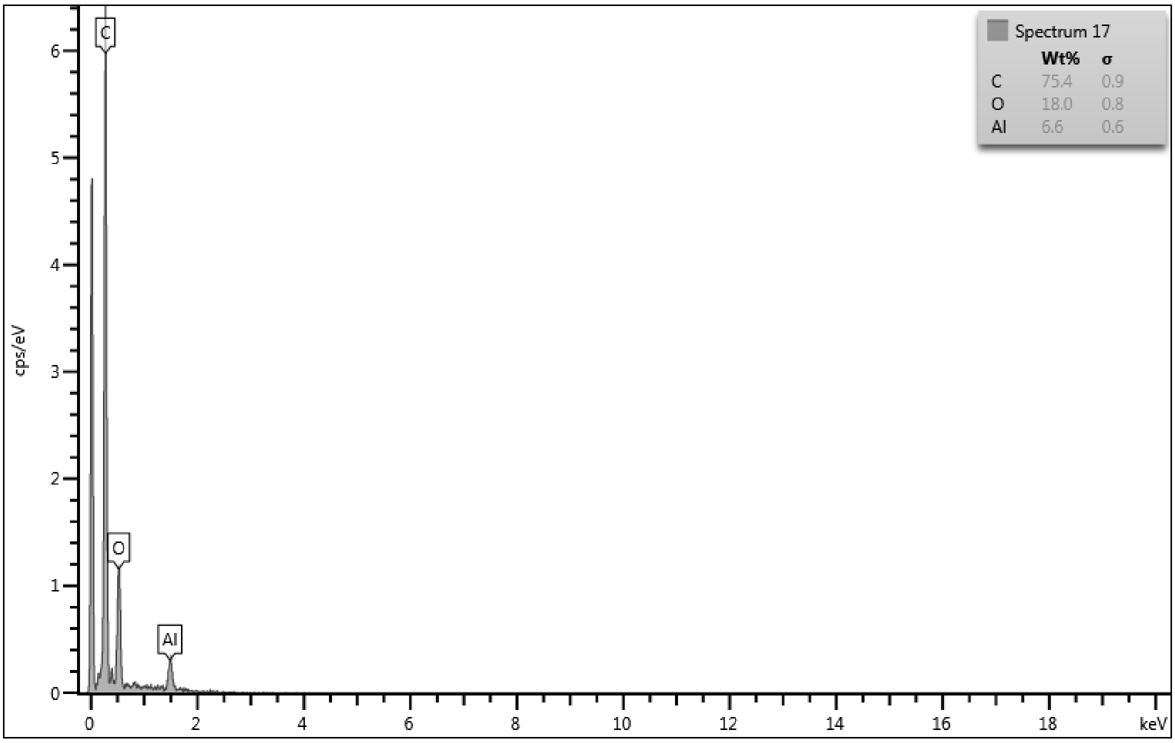

Figure A 3 Spectrum 17 was taken on the surface matching the rivet head location

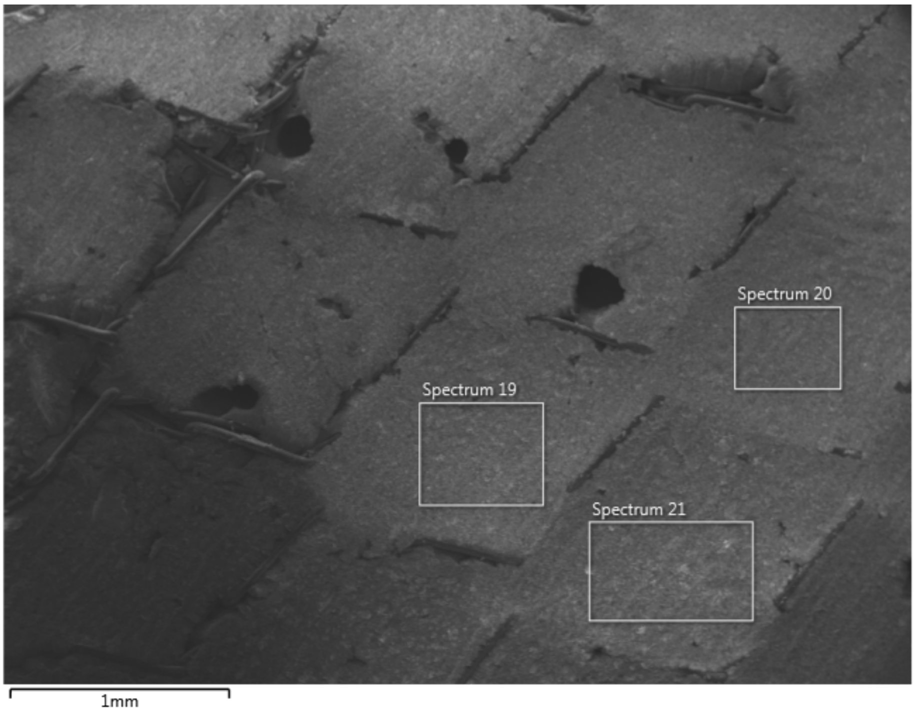

Figure A 4 Spectra 20 and 21 were taken away from the rivet head location

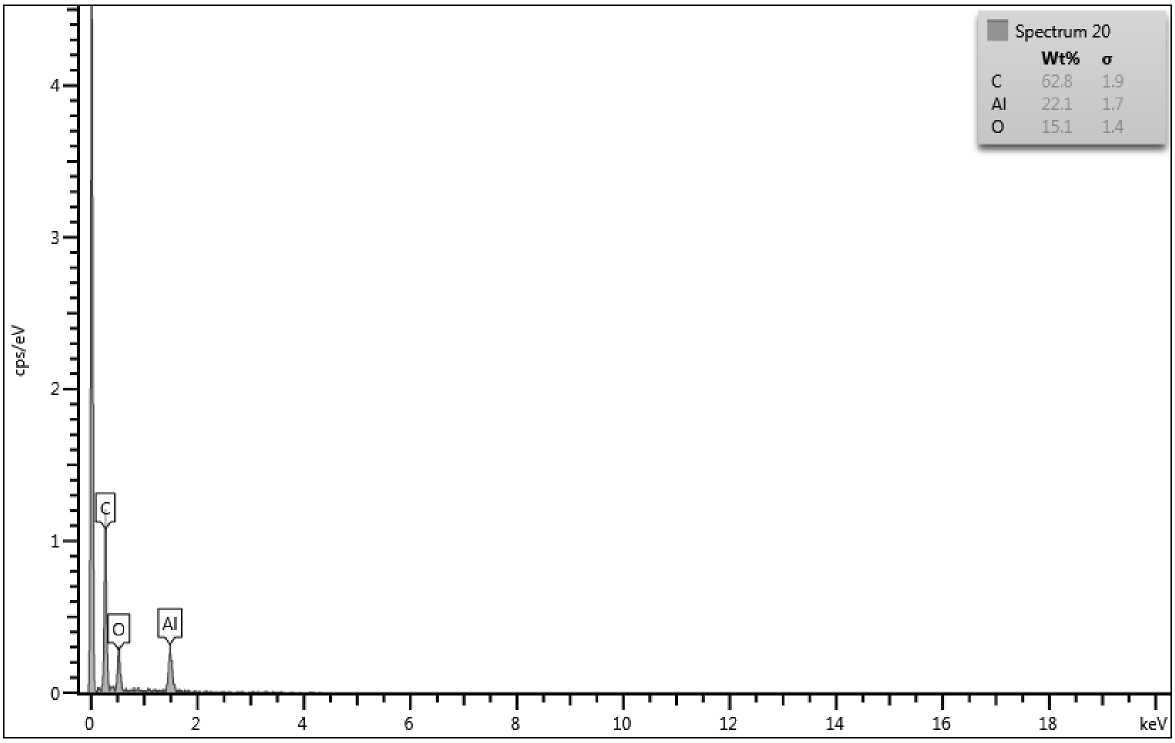

Figure A 5 Spectrum 20 was taken on the surface away from the rivet head location

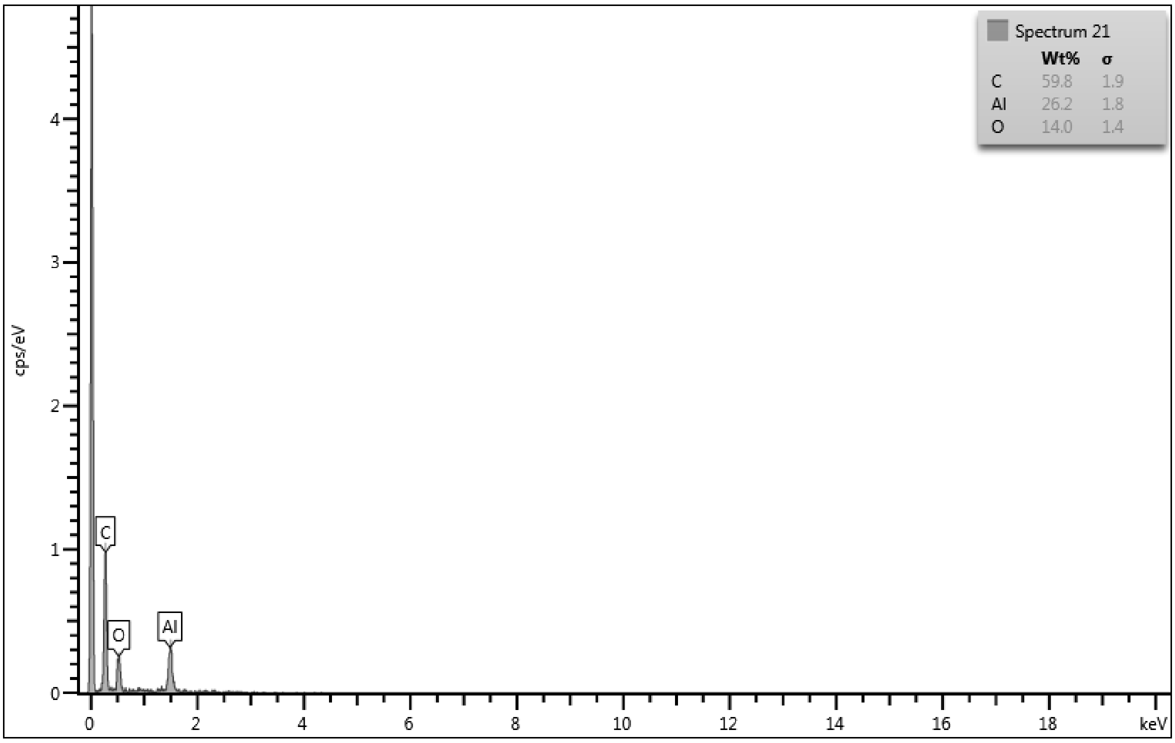

Figure A 6 Spectrum 21 was taken on the surface away from the rivet head location

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It is estimated that over 5,000 adhesively bonded repairs (ABRs) have been applied to the Royal Australian Air Force (RAAF) F-111 aircraft over the last twenty five years, mainly to honeycomb sandwich panels. Retirement of the fleet in December 2010 presented a unique opportunity to evaluate the integrity of a large number of airworthy ABRs. Consequently, DSTO in partnership with the RAAF, through ASI at DGTA and with the assistance of Boeing Australia developed a program to assess the condition of the F-111 ABRs. The F-111 Adhesive Bonded Repair Assessment Program (FABRAP) was established in mid 2010 and initial field testing was carried out from October 2010. The current report provides an update on the analysis of the results from the field level testing undertaken between October 2010 and July 2012 on repairs to honeycomb structure which used FM300-2K adhesive and RAAF approved surface treatments and application procedures. The investigation indicates that when repairs were applied according to RAAF procedures and with qualified technicians in fit-for-purpose facilities, that bond strength did not degrade as a result of either long term environmental exposure or service exposure or both.</td></tr>
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